AEDC-TR-69-42

COMPUTER ANALYSIS OF THE RELATIVE FLOW IN THE BLUNT-TRAILING-EDGE SUPERSONIC COMPRESSOR BLADING

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May 1969

ENGINEERING SUPPORT FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was sponsored by the Aerospace Research Laboratories, Office of Aerospace Research, under Program Element 61102F, Project 7065.

The results of research presented were obtained by ARO, Inc., (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center under Contract F40600-69-C-0001. The research was conducted from April 1967 to December 1968 under ARO Project TW5901. The manuscript was submitted for publication on January 20, 1969.

The author, J. W. Salvage, is a research assistant at the University of Tennessee Space Institute assigned to ARO, Inc., under ARO subcontract to UTSI 69-29-TS/OMD.

The author is indebted to Mr. F. Worthy for his efforts in programming the major portion of the computations and to Mr. M. M. Solomon who successfully completed the programming. Grateful appreciation is also due Mr. C. T. Carman for his confidence in the endeavor. Thanks are due Drs. A. J. Wennerstrom and B. H. Goethert for their advice and Mr. J. M. Myers for his assistance.

The program described in this report was written to aid in analyzing the performance of the blunt-trailing-edge supersonic compressor and as partial fulfillment of the requirements for a Masters Degree at UTSI.

This technical report has been reviewed and is approved.

Hans K. Doetsch Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

The computer program presented in this report has been designed specifically for the analysis of the blunt-trailing-edge supersonic compressor. Beginning with flow property measurements obtained in a non-rotating coordinate system, streamtube boundaries are determined at each measuring plane. Then mass-averaged values of the flow properties in each streamtube are translated to a coordinate system rotating with the compressor rotor, and a particular one-dimensional flow model is imposed on each streamtube to describe the flow process through the rotor. The flow model includes analysis of shock loss and sudden expansion loss leading to an estimate of the additional loss occurring within the flow field of the rotor. Various other calculations are presented which are aimed at the analysis of data for accuracy and consistency.

CONTENTS

NOMENCLATURE

A	Area
A_i	Coefficients of a curve describing inlet rotor blade angle as a function of radius (i = 1,..., 6)
a, b, c, d	Coefficients of a curve describing enthalpy as a function of temperature
B	Blockage factor
B_i	Coefficients of a curve describing suction surface expansion as a function of radius (i = 1,..., 5)
C_1	Passage shock loss adjustment coefficient

C_2	Passage shock static pressure rise adjustment coefficient
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
$\bar{c}$	Isentropic coefficient, $(\bar{\kappa} - 1)/\bar{\kappa}$
D	Diffusion factor
D_i	Coefficients of a curve describing the exit blade angle as a function of radius (i = 1, . . . , 6)
$d'(\ )$	Indicates change along a streamline
E_i	Coefficients of a curve describing the blade-trailing-edge thickness as a function of radius (i = 1, . . . , 5)
F_i	Coefficients of a curve describing the blade solidity as a function of radius (i = 1, . . . , 5)
g_c	Conversion factor making Newton's Second Law consistent in units (32.1740 lbm-ft/lbf-sec^2)
H	Total enthalpy
J	Mechanical equivalent of heat (777.97 ft-lbf/Btu)
M	Mach number
MM	Number of streamtubes
m	Mass flow
N	Number of measurements supplied in each measuring plane
NN	Number of measurements supplied in the downstream traverse measuring plane
n	Number of blades on the rotor
P	Total pressure
PL	Profile loss parameter
p	Static pressure
R	Gas constant for air (1715.608 ft^2/sec^2-°R)
RF	Temperature probe recovery factor
R_p	Total pressure ratio
r	Radial distance from the rotor axis
T	Total temperature
t	Static temperature

th	Blade-trailing-edge thickness
V	Absolute velocity
x	Fractional portion of the annulus height
α	Absolute flow angle, angle between absolute velocity and axial direction
β	Relative flow angle, angle between relative velocity and axial direction
β'	Blade angle, angle between blade camber line and axial direction
δE	Change in energy across the rotor
δH	Change in total enthalpy across the rotor
δm	Change in mass flow across the rotor
η	Efficiency
θ	Rotations per minute of rotor
κ	Ratio of specific heats, c_p/c_v
$\bar{\kappa}$	Temperature averaged specific heat ratio
ν	Prandtl-Meyer expansion angle
σ	Blade solidity, ratio of blade chord to blade spacing
ϕ	Angle of surface expansion
ω	Total pressure loss parameter
Ω	Rotor angular speed

SUBSCRIPTS

a	Axial component.
ad	Adiabatic
av	Arithmetic average
c	Corrected or calculated
E	Rotor exit conditions
h	Hub, inner casing
i	A counter designating the radial measuring stations
iB	Radial position counters locating streamtube boundaries

id	Ideal (no loss) conditions
is	Isentropic
i*	Radial position counter locating streamtube centers and boundaries
j	Designation of the axial measuring planes
= 1	Implies the measuring plane at rotor inlet
= 2	Implies the measuring plane at rotor exit in which traverse measurements are made (This counter is also used to imply downstream conditions in general.)
= 3	Implies the measuring plane at rotor exit in which rake measurements are made
m	Streamtube counter implying mass-averaged conditions of that streamtube
P	Profile
PS	Passage shock
SE	Sudden expansion
SS	Suction surface
T	Based on stagnation conditions
t	Tip, outer casing
θ	Tangential component

SUPERSCRIPTS

/	Relative to the rotor
*	Critical conditions

SECTION I
INTRODUCTION

The computer program described herein has been developed for the IBM 360/50 in an attempt to extend the capability of data analysis for the supersonic blunt-trailing-edge compressor at the Arnold Engineering Development Center. An example of a typical compressor blade profile is shown in Fig. 1 (Appendix I). The program is intended primarily to give some insight into the flow process through a compressor rotor viewed as if the observer were rotating with the angular velocity of the rotor. In general, theoretical techniques must be used to determine the flow in a rotating passage since it is not mechanically possible to place a probe within the rotor.

The problem is approached basically from the streamtube point of view. If flow is assumed steady and axisymmetric and if the radial height of the blade is divided into small enough increments so that the radial variation within the increment is small, then it should be possible to consider the flow through the rotor as one-dimensional within each streamtube. Strictly speaking, this method demands further that secondary flow effects, such as radial mass transfer, be negligible.

The model for the composition of the relative total pressure losses in a streamtube is quite similar to that proposed in Ref. 1 for flow in transonic compressors. In addition to the losses resulting from shock waves and the viscous effects along the blade profile as suggested in Ref. 1, the blunt-trailing-edge blading may be expected to have additional loss caused by the abrupt area increase at the blade trailing edge. The general validity of such a model has been demonstrated in Ref. 2.

The sections of this report include a description of the computer input (Appendix II), presentation of the equations used in the computation, and a description of the output from the program (Appendix III) The program is written in FORTRAN IV.

SECTION II
THE EQUATIONS AND THE COMPUTATIONAL SCHEME

In general, the equations of this section outline step-by-step the process of the computation. The procedure is, basically, to determine the boundaries and centers of a selected number of steamtubes, MM, using data measured in an absolute frame of reference, then to mass

average the measured data between streamtube boundaries and to consider these average values as concentrated at the center of the streamtube. The averaged values are then translated to a frame of reference rotating with the angular velocity of the rotor. The flow model described in Refs. 2 and 3 is then used to determine additional loss unaccounted for in the model. Correlation of this additional loss remains the basic problem of the analyst.

In addition to the main objective of the program, described above, several additional computations have been included to provide checks on the results of experiments and to enlarge the use of the existing data.

2.1 ASSUMPTIONS

1. The flow of air as a weightless, thermally perfect gas is assumed to be frictionless, time-steady, adiabatic, and axisymmetric as determined from discrete point measurements of the flow variables.
2. Radial mass transfer across streamtube boundaries is ignored.
3. Five discrete points are selected for measurement of the flow properties in front of the wheel.
4. Behind the wheel two different sets of measurements may be used to independently describe the flow at the same axial plane of measurement. In the tests at AEDC this capability has been used to evaluate separate measurements made by single-probe traverse and multi-probe rake. Traverse measurements may be supplied at either 5 or 11 discrete points in the flow field. Rake measurements are supplied at only 5 points.
5. In one specific situation the two sets of measurements behind the wheel may be obtained at different axial planes. This particular condition is differentiated by the capability of entering exactly 13 discrete point measurements for the traverse. The set of data for the rake will still contain measurements at only 5 discrete points.
6. Discrete point measurements of total pressure, absolute flow angle, and total temperature may be entered in all three measuring planes at 5 points. When traverse measurements are made at 11 or 13 points, only total pressure

and absolute flow angle are obtained. Total temperature is obtained at only 5 points in the midportion of the flow field and not in the extra points traversed in the boundary layer. The extra total temperatures necessary for calculations are obtained in the program by extrapolation.

7. Static pressure is measured at the walls at the axial planes of the other flow property measurements. The static pressure is assumed to vary linearly across the annulus to obtain values at the discrete points of measurement.

2.2 DETERMINATION OF THE PROFILES FOR STATIC AND TOTAL PRESSURE, TOTAL TEMPERATURE, AND THE ABSOLUTE FLOW ANGLE

The inlet measuring plane, designated by the subscript $j = 1$, is assumed to be located near enough to the leading edge of the rotor blades so that flow conditions at the measuring plane may be considered representative of conditions immediately ahead of the rotor leading edge. The downstream measuring planes, designated $j = 2$ for measurements obtained by traverse and $j = 3$ for measurements obtained by rakes, are assumed to be far enough downstream so that conditions may be considered axisymmetric. The planes of measurement are assumed to be perpendicular to the compressor axis.

In each measuring plane a number of radial positions, N_j, are chosen as points at which measurements are made of total pressure, total temperature, and absolute flow angle. Static pressure is measured at the wall in the same axial plane and is assumed to vary linearly across the annulus. A more complete description of the measuring techniques and the general layout of the supersonic compressor testing facility is described in Ref. 4. For $j = 1$ or 3, N_j has the value of 5. For $j = 2$, N_j may have the value of 5, 11, or 13 corresponding to NN in the input data. The radial location of the i-th measuring station in the j-th measuring plane is given by

$$r_{ji} = r_{jh} + x_{ji}(r_{jt} - r_{jh}), \qquad j = 1, 2, 3, \; i = 1, 2, \ldots, N_j, \; 0 \le x_{ji} \le 1 \tag{1}$$

where r_{jh} is the radius in inches of the inner casing wall (hub wall), r_{jt} is the radius in inches of the outer casing wall (tip wall), and where x_{ji} may be interpreted as the location of the measuring station in terms of the fractional part of annulus height. The quantities r_{jh}, r_{jt}, and x_{ji} are input data.

Static pressure measurements are taken on the inner (h) and outer (t) casing walls. The assumption of straight line variation across the

annulus implies that the static pressure at any x_{ji} may be calculated by the equation

$$p_{ji} = p_{jh} + x_{ji}(p_{jt} - p_{jh}), \quad j = 1, 2, 3, \; i = 1, 2, \ldots, N_j, \; 0 \leq x_{ji} \leq 1 \tag{2}$$

When N_j equals 5, the static pressure is calculated for two additional points at x_{ji} equal to 0.05 and 0.95.

Because of the physical requirement of no "slip" at a wall, the flow velocity at a wall must be zero. For this reason the static and total pressures are equivalent at a wall; i.e.,

$$\left.\begin{aligned} P_{ji} &= p_{jh}, \quad i = h \\ P_{ji} &= p_{jt}, \quad i = t \end{aligned}\right\} \quad j = 1, 2, 3 \tag{3}$$

The drop in total pressure from its inviscid value occurs rapidly in the wall boundary layer. In the cases of N_2 = NN = 11 or 13, a number of total pressure measurements have been made in the boundary-layer region so that, together with relations(3), a complete total pressure profile may be approximated. In the cases of N_j = NN = 5 the data are insufficient to allow accurate mass flow calculations across the annulus. Therefore, two additional points, located at x_{ji} equal to 0.05 and 0.95, are supplied using an empirically estimated relation based on the more accurate boundary-layer surveys. The value for N_j has thus been increased from 5 to 7 for these cases; i.e., 5 actual measurements in the flow field entered by input data plus 2 extrapolated points.

In every case, total temperature is obtained only at the five measuring stations in the midportion of the annulus. To obtain the extra values necessary for computation, a second degree polynomial is fit to the three measured points nearest the locations where the values are needed.

For the cases when it is necessary to estimate the total pressure at x_{ji} = 0.05 or 0.95, it is also necessary to supply an estimate of the absolute flow angle at these points. The boundary-layer traverses have shown that it is sufficiently accurate to assume a straight line fit of the two points nearest the annulus wall considered.

2.3 DETERMINATION OF THE ABSOLUTE MACH NUMBER, TOTAL AND STATIC TEMPERATURE CORRECTED FOR PROBE RECOVERY FACTOR, AND THE RATIO OF SPECIFIC HEATS

The specific heat at constant pressure, c_p, is slightly temperature dependent. For air, using the data of Ref. 5, a third-order polynomial

was found to fit very well for the temperature range of interest, 400 to 900°R, i.e.,

$$c_p\,[\mathrm{Btu/lbm\ °R}] = a - bt + ct^2 - dt^3 \tag{4}$$

with

$$\begin{aligned} a &= 0.241883 \\ b &= -1.22830 \times 10^{-5} \\ c &= 1.15098 \times 10^{-8} \\ d &= 7.75163 \times 10^{-12} \end{aligned} \tag{5}$$

where t is entered in degrees Rankine. Multiplying the result by g_cJ to obtain units of $ft^2/sec^2°R$ implies that the ratio of specific heats, κ, may be calculated by

$$\kappa = c_p/(c_p - R) \tag{6}$$

The absolute Mach number is calculated by

$$M = \sqrt{\frac{2}{\kappa - 1}\left[\left(\frac{P}{p}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]}^{\,1/2} \tag{7}$$

Correction of the measured and extrapolated total temperatures for the probe recovery factor, RF, may be accomplished by

$$T_c = \frac{T\,(\kappa M^2 - M^2 + 2)}{RF\,(\kappa M^2 - M^2) - 2} \tag{8}$$

The static temperature is then given by

$$t = T_c \left(\frac{p}{P}\right)^{\frac{\kappa-1}{\kappa}} \tag{9}$$

Beginning with an initial guess on the static temperature in Eq. (4), an iteration process is carried out with Eqs. (4) to (9) until Eq. (9) is satisfied to the accuracy of the machine for each measuring station, i, in every measuring plane, j.

2.4 DETERMINATION OF THE TANGENTIAL AND AXIAL COMPONENTS OF VELOCITY FOR PLOTTING

The absolute velocity may now be calculated using the equation

$$V_{ji} = \sqrt{\kappa_{ji} R\, t_{ji}}\; M_{ji},\; j = 1, 2, 3,\; i = t, 1, 2, \ldots, N_j, h \tag{10}$$

The axial and tangential components of the absolute velocity are then given, respectively, by

$$\left.\begin{aligned} V_{aji} &= V_{ji} \cos \alpha_{ji} \\ \text{and} \quad V_{\theta ji} &= V_{ji} \sin \alpha_{ji} \end{aligned}\right\} \tag{11}$$

where $j = 1, 2, 3,\ i = t, 1, 2, \ldots, N_j, h$.

For J = 2 and 3 the ratios of V_{aji} and $V_{\theta ji}$ to the maximum axial velocity are plotted versus annulus height when ~~IPLOT~~ is ~~1~~ or 3. An example of the plot is shown in Fig. 2. IPT 2

2.5 DETERMINATION OF THE RADIAL POSITION OF STREAMTUBE BOUNDARIES AND CENTERS

In each measuring plane, j, the annulus is to be divided into a number of areas, MM, through which equal mass flows, where MM is input data. The mass average of the flow properties in each of the MM areas is determined and is considered to be concentrated at the radius representing the center of mass of each area.

The axial mass flow per unit area is given by

$$\left(\frac{m}{A}\right)_{ji} = g_c \sqrt{\frac{\kappa_{ji}}{R}} \; \frac{P_{ji}\, M_{ji}}{\sqrt{T_{cji}}} \left(1 + \frac{\kappa_{ji} - 1}{2} M_{ji}^2\right)^{1/2} \cos \alpha_{ji} \tag{12}$$

for $j = 1, 2, 3,\ i = t, 1, 2, \ldots, N_j, h$. The total mass flow at each measuring plane, m_j, is calculated using the equation

$$m_j = 2\pi \int_{r_{jh}}^{r_{jt}} r \left(\frac{m}{A}\right) dr, \quad j = 1, 2, 3 \tag{13}$$

The quantities m_j are printed out on output data PAGE 5 in Appendix III for flow continuity checks and comparison with other methods of mass flow measurements.

Beginning with $r_{ji*} = r_{jt}$, 2(MM) - 1 radii are determined satisfying the relation

$$2\pi \int_{r_{ji^*+1}}^{r_{ji^*}} r \left(\frac{m}{A}\right) dr = \frac{m_j}{2(MM)} \tag{14}$$

If the convention is adopted that i* equals zero when $r_{ji*} = r_{jt}$, then the radii of the streamtube centers are given when i* is odd and the streamtube boundaries are given when i* is even. The radii in terms of annulus height may be given by

$$x_{ji^*} = \frac{r_{ji^*} - r_{jh}}{r_{jt} - r_{jh}}, \; j = 1, 2, 3,\ i^* = t, 1, 2, \ldots, 2(MM) - 1, h \tag{15}$$

Both r_{ji*} and x_{ji*} are printed on the output data PAGE 2 (Appendix III).

In an effort to check the accuracy with which the integrations have been performed, the integral of the mass flow between $r_{j2(MM)-1}$ and r_{jh}

is calculated and compared with the amount which should remain; i.e.,

$$\%\,\delta m_j = \frac{\dfrac{m_j}{2(MM)} - 2\pi \displaystyle\int_{r_{jh}}^{r_{j2(MM)-1}} r\left(\frac{m}{A}\right) dr}{\dfrac{m_j}{2(MM)}} \times 100,\ j = 1,2,3 \tag{16}$$

These quantities are printed on output data PAGE 5 in Appendix III.

2.6 DETERMINATION OF MASS-AVERAGED STREAMTUBE FLOW PROPERTIES

A measured flow property may be mass averaged between the boundaries of a streamtube using the equation

$$\bar{q}_{jm} = \frac{\displaystyle\int_{r_{jiB+1}}^{r_{jiB}} q\, r\left(\frac{m}{A}\right) dr}{\displaystyle\int_{r_{jiB+1}}^{r_{jiB}} r\left(\frac{m}{A}\right) dr},\ j = 1, 2, 3,\ m = 1, 2, \ldots, MM \tag{17}$$

where the counter iB is varied so that radii bounding the m-th streamtube are used. The quantity q may be the static pressure, total pressure, or To the absolute flow angle; and $\bar{q}$ represents the mass average of that quantity. The results of mass averaging are printed on output data PAGE 3 in Appendix III. The equivalent one-dimensional average over the annulus height of each property may be computed by

$$\bar{q}_j = \frac{1}{MM}\sum_{m=1}^{MM} \bar{q}_{jm},\ j = 1, 2, 3 \tag{18}$$

These results are also printed on output data PAGE 3 in Appendix III.

Using the mass-averaged values of static and total pressure and total temperature and Eqs. (4), (5), (6), and (9), an iteration cycle is set up to yield an estimate of the mass-averaged values of the static temperature and the ratio of specific heats. Then Eq. (7) is used to calculate the streamtube average absolute Mach number.

In the following description, a quantity with a subscript m implies the streamtube mass average of that quantity. The subscript i will be retained to indicate input data or calculations at the radial measuring stations.

2.7 CALCULATIONS TO CHECK THE BALANCE OF THE ENERGY EQUATION FOR ADIABATIC FLOW

If the total enthalpy is defined

$$H = \int_0^T c_p \, dT$$

then the streamtube total enthalpy may be calculated

$$H_{jm} = aT_{jm} + \frac{b}{2} T_{jm}^2 + \frac{c}{3} T_{jm}^3 + \frac{d}{4} T_{jm}^4 \tag{19}$$

for j = 1, 2, 3, m = 1, 2, ... , MM, in units of Btu/lbm, where the coefficients a, b, c, and d are given in Eq. (5). The change in total enthalpy through a streamtube is the given by

$$\delta H_{jm} = H_{jm} - H_{1m}, \; j = 2, 3, \; m = 1, 2, \ldots, MM \tag{20}$$

These quantities are printed on output PAGE 5 in Appendix III.

The streamtube average absolute velocity is given by an equation similar to (10) with κ_{ji}, t_{ji}, and M_{ji} replaced by, respectively, the mass-averaged values of the ratio of specific heats, static temperature, and absolute Mach number. The streamtube average of the tangential velocity is then given by

$$V_{\theta jm} = \frac{V_{jm}}{g_c \, J} \sin \alpha_{jm} \tag{21}$$

for j = 1, 2, 3, m = 1, 2, ... , MM, in units of Btu sec/lbm-ft.

The energy equation for adiabatic flow with work addition may be written

$$d'H = \Omega \, d'(rV_\theta)$$

where the symbol d′( ) indicates change along a streamline. The wheel angular speed, Ω, in units of $\sec^{-1}$, is given by

$$\Omega = \frac{2 \pi \theta}{60 \text{ sec/min}} \tag{22}$$

where θ is the wheel RPM and is supplied by input data. The degree of balance of the energy equation may be represented by

$$\delta E_{jm} = H_{jm} - H_{1m} - \frac{\Omega}{12\left(\frac{\text{in.}}{\text{ft}}\right)} \left(r_{jm} V_{\theta jm} - r_{1m} V_{\theta 1m}\right) \tag{23}$$

for j = 2, 3, m = 1, 2, . . . , MM. The percentage of balance is calculated by

$$\left(\% \frac{\delta E}{\delta H}\right)_{jm} = \frac{\delta E_{jm}}{\delta H_{jm}} \times 100, \; j = 2, 3, \; m = 1, 2, \ldots, MM \tag{24}$$

This representation of the balance of the energy equation is printed on output data PAGE 5 in Appendix III along with the change in total enthalpy

through the corresponding streamtube. The one-dimensional average of these quantities is also presented.

2.8 CALCULATION OF STREAMTUBE TOTAL PRESSURE RATIO AND EFFICIENCY

The streamtube total pressure ratio is given by the relation

$$R_{pjm} = \frac{P_{jm}}{P_{1m}},\ j = 2, 3,\ m = 1, 2, \ldots, MM \tag{25}$$

This quantity, along with its equivalent one-dimensional average calculated by Eq. (18), is printed on output data PAGE 6 in Appendix III.

A temperature-averaged specific heat ratio, $\bar{\kappa}_{jm}$, is calculated by

$$\bar{\kappa}_{jm} = \frac{\int_{T_{1m}}^{T_{jm}} \frac{c_p}{c_p - R}\, dT}{T_{jm} - T_{1m}},\ j = 2,3,\ m = 1,2,\ldots, MM \tag{26}$$

for use in evaluating streamtube efficiency.

Adiabatic efficiency is defined by the equation

$$\eta_{ad} \equiv \frac{\delta H_{is}}{\delta H}$$

where δH_{is} is the isentropic enthalpy rise and δH is the actual enthalpy rise. Defining the isentropic coefficient $\bar{c}_{jm}$ by

$$\bar{c}_{jm} = \frac{\bar{\kappa}_{jm} - 1}{\bar{\kappa}_{jm}},\ j = 2, 3,\ m = 1, 2, \ldots, MM \tag{27}$$

then the isentropic enthalpy rise is given by

$$(\delta H_{is})_{jm} = a\, T_{1m}\, [(R_{pjm})^{\bar{c}_{jm}} - 1] + \frac{b}{2}\, T_{1m}^2\, [(R_{pjm})^{2\bar{c}_{jm}} - 1] + \frac{c}{3}\, T_{1m}^3\, [(R_{pjm})^{3\bar{c}_{jm}} - 1] + \frac{d}{4}\, T_{1m}^4\, [(R_{pjm})^{4\bar{c}_{jm}} - 1] \tag{28}$$

for j = 2, 3, m = 1, 2, . . . , MM, where the coefficients a, b, c, and d are given in Eq. (5). The streamtube adiabatic efficiency is then given by

$$\eta_{adjm} = \frac{(\delta H_{is})_{jm}}{H_{jm} - H_{1m}}\ j = 2,3,\ m = 1, 2, \ldots, MM \tag{29}$$

This quantity and its equivalent one-dimensional average are printed on output data PAGE 6 in Appendix III.

2.9 DETERMINATION OF THE FLOW PROPERTIES IN RELATIVE COORDINATES

The streamtube average tangential component of the relative Mach number, $M'_{\theta jm}$, is given by

$$M'_{\theta jm} = \frac{2 \pi \theta r_{jm}}{\left(12 \frac{in.}{ft}\right) 60 \left(\frac{sec}{min}\right) \sqrt{\kappa_{jm} R t_{jm}}} - M_{jm} \sin \alpha_{jm} \tag{30}$$

for j = 1, 2, 3, m = 1, 2,. . . , MM. The average relative Mach number is then given by

$$M'_{jm} = [M'^2_{\theta jm} + (M_{jm} \cos \alpha_{jm})^2]^{1/2} \tag{31}$$

for the same range of j and m.

The streamtube average relative flow angle, β_{jm}, is given by

$$\beta_{jm} = \arctan \left(\frac{M'_{\theta jm}}{M_{jm} \cos \alpha_{jm}}\right) \tag{32}$$

for j = 1, 2, 3, m = 1, 2, 3, . . . , MM.

The relative total temperature and total pressure are given, respectively, by

$$T'_{jm} = T_{jm} \left[\frac{1 + \frac{\kappa_{jm} - 1}{2} M'^2_{jm}}{1 + \frac{\kappa_{jm} - 1}{2} M^2_{jm}}\right] \tag{33}$$

$$P'_{jm} = p_{jm} \left(1 + \frac{\kappa_{jm} - 1}{2} M'^2_{jm}\right)^{\frac{k_{jm}}{k_{jm}-1}} \tag{34}$$

for j = 1, 2, 3, m = 1, 2,. . . , MM.

The relative Mach number, flow angle, total pressure, and total temperature are printed for each streamtube and each measuring plane on output data PAGE 4 in Appendix III.

2.10 CALCULATION OF THE OVERALL RELATIVE TOTAL PRESSURE LOSS

In the preceding sections the main objective has been to locate a number of streamtubes and determine the average relative flow properties in each streamtube before and after the rotor. The objective becomes now that of attempting to fit the flow model to the experimental results.

To the benefit of centrifugal-type turbomachinery, a flowing fluid may do work or be worked upon by simply changing the distance of

streamlines from the axis of the turbomachine. To correct for this fact in calculating the overall relative total pressure loss for an axial-flow machine, the ideal (no loss) relative total pressure ratio is given by

$$(R'_{pjm})_{id} \equiv \left(\frac{P'_{jm}}{P'_{1m}}\right)_{id} = \left\{1 + \frac{\kappa_{avjm} - 1}{2} M^2_{Tjm}\left[1 - \left(\frac{r_{1m}}{r_{jm}}\right)^2\right]\right\}^{\frac{\kappa_{avjm}}{\kappa_{avjm}-1}} \tag{35}$$

for j = 2, 3, m = 1,2,..., MM from Ref. 6, where $\kappa_{avjm} = \frac{\kappa_{jm} - \kappa_{1m}}{2}$

where M_{Tjm} is the ratio of the outlet element wheel speed to the inlet relative stagnation velocity; i.e.,

$$M_{Tjm} = \frac{\Omega\, r_{jm}}{\sqrt{\kappa'_{Tm} R T'_{1m}}},\quad j = 2, 3\ m = 1, 2, \ldots, MM \tag{36}$$

where κ'_{Tm} is the specific heat ratio based on the inlet relative total temperature. The overall relative total pressure loss is then given by

$$\bar{\omega}'_{jm} = (R'_{pjm})_{id}\left[\frac{1 - \dfrac{\left(\frac{P'_{jm}}{P'_{1m}}\right)}{(R'_{pjm})_{id}}}{1 - \dfrac{p_{1m}}{P'_{1m}}}\right] \tag{37}$$

also from Ref. 6. This quantity is printed on output data PAGE 6 in Appendix III.

The overall relative total pressure loss is assumed to be the sum of shock loss, profile loss, and loss attributable to sudden area expansion at the trailing edge. Shock loss and sudden area expansion loss may be estimated under certain assumptions. The profile loss must be obtained by subtraction of these values from the overall loss, and then correlated.

2.11 CALCULATION OF SHOCK LOSSES

Pseudo-normal shock diffusion is inherent in the conception of the blunt-trailing-edge compressor blading. At maximum back pressure the losses caused by a pseudo-normal shock system, neglecting viscous interaction, cannot be greater than the loss of a single normal shock at the same inlet conditions. The passage inlet Mach number of the compressor is assumed to be the average of the blade inlet relative Mach number, M'_{1m}, and the suction surface Mach number at the entrance to the passage, M_{SSm}. The Prandtl-Meyer angle, ν, of M_{SSm} is given by

$$\nu(M_{SS\,m}) = \nu(M'_{1m}) + \beta_{1m} - \beta'_{1m} + \phi_{SSm} \tag{38}$$

if $M'_{1m} \geq 1.0$, where $\nu(M'_{1m})$ is the Prandtl-Meyer angle of the inlet relative Mach number, where $\beta_{1m} - \beta'_{1m}$ is the amount of turning required for the inlet relative flow to become tangent to the blade surface at the leading edge, and where ϕ_{SSm} is the angle of expansion from the leading edge to passage entrance.

The Prandtl-Meyer angle, ν, for a Mach number, M, is calculated by

$$\nu = \sqrt{\frac{\kappa + 1}{\kappa - 1}} \arctan \sqrt{\frac{\kappa - 1}{\kappa + 1} (M^2 - 1)} - \arctan \sqrt{M^2 - 1} \tag{39}$$

Therefore, $\nu(M'_{1m})$ is easily determined by this equation; but $\nu(M_{SSm})$, given by Eq. (38), requires iteration to obtain M_{SSm} from Eq. (39).

The inlet blade angle, β'_1, is assumed to be described by an arbitrary function of the form

$$\beta'_1 = \frac{A_1}{r^2} + \frac{A_2}{r} + A_3 + A_4 r + A_5 r^2 + \arctan (A_6 r) \tag{40}$$

where the coefficients are input data. Suction surface expansion, ϕ_{SS}, is assumed to be described by a similar function

$$\phi_{SS} = \frac{B_1}{r^2} + \frac{B_2}{r} + B_3 + B_4 r + B_5 r^2 \tag{41}$$

where the coefficients are input data.

The passage entrance Mach number is given by

$$M_{avm} = \frac{M'_{1m} + M_{SSm}}{2} \tag{42}$$

This quantity is printed on output data PAGE 6 in Appendix III.

The total pressure ratio across a normal shock with upstream Mach number M_{avm} is given by

$$R_{PSm} = \left[1 + \frac{2\kappa_{1m}}{\kappa_{1m} + 1} (M^2_{avm} - 1)\right]^{-\frac{1}{\kappa_{1m} - 1}} \left[\frac{(\kappa_{1m} + 1) M^2_{avm}}{(\kappa_{1m} - 1) M^2_{avm} + 2}\right]^{\frac{\kappa_{1m}}{\kappa_{1m} - 1}} \tag{43}$$

The loss caused by the pseudo-normal shock system, neglecting viscous interaction, is then given by

$$\omega'_{PSm} = C_1 \left[\frac{1 - R_{PSm}}{1 - \frac{p_{1m}}{P'_{1m}}}\right], \; m = 1, 2, \ldots, MM \tag{44}$$

where C_1 is a correction factor supplied in the input data and used to adjust for the fact that the shock system may not produce normal shock loss. Generally, C_1 is approximately 0.9.

For transonic flow with high subsonic inlet relative Mach numbers, shocks may also be expected to occur. Total pressure losses attributable to these shocks may be estimated, similar to Ref. 7, by calculating M_{SSm} based on

$$\nu(M_{SSm}) = \phi_{SSm}$$

rather than Eq. (38). If M_{avm}, calculated by Eq. (42), is greater than one, shock loss is calculated through Eqs. (43) and (44); if M_{avm} is less than or equal to one, no shock loss is assumed to occur.

The passage shock loss, ω'_{PSm}, is printed on output data PAGE 6 in Appendix III.

The static pressure through the normal shock system is given by

$$p_{PSm} = C_2 \, p_{1m} \left[1 + \frac{2\kappa_{1m}}{\kappa_{1m} + 1} \left(M^2_{avm} - 1 \right) \right] \quad m = 1, 2, \ldots MM \tag{45}$$

where C_2 is a correction factor supplied in the input data. This quantity is printed on output data PAGE 5 in Appendix III for comparison with experiment and the results of sudden area expansion calculations.

2.12 CALCULATION OF THE LOSS ATTRIBUTABLE TO SUDDEN AREA EXPANSION FOR CYLINDRICAL STREAM SURFACES

In order to use the results of Ref. 8, it is necessary to assume that the streamlines, represented by the streamtube centers, lie on circular cylinders between the plane of the trailing edge and the downstream measuring planes (j = 2 or 3). Such an assumption implicitly demands that radial shift of the streamlines, if such shift occurs, takes place entirely within the rotor.

The flow is assumed to leave the rotor at an average angle equal to the rotor exit blade angle, β'_E, given as a function of radius by

$$\beta'_E = \frac{D_1}{r^2} + \frac{D_2}{r} + D_3 + D_4 r + D_5 r^2 + \arctan(D_6 r) \tag{46}$$

where the coefficients are input data.

The critical relative Mach number at the downstream measuring planes (j = 2, 3) is given by

$$M'^{*}_{jm} = \left[\frac{\frac{\kappa_{jm}+1}{2} M'^{2}_{jm}}{1+\frac{\kappa_{jm}-1}{2} M'^{2}_{jm}}\right]^{1/2} \tag{47}$$

The critical Mach number of the relative flow at the trailing-edge plane is then given by

$$M'^{*}_{Ejm} = M'^{*}_{jm} \frac{\sin\beta_{jm}}{\sin\beta'_{Ejm}}, \; j = 2, 3, \; m = 1, 2, \ldots, MM \tag{48}$$

where β'_{Ejm} is calculated for $r = r_{jm}$, the radius of the center of the m-th streamtube for measurements in the j-th plane.

The relative Mach number at the trailing-edge plane is then given by

$$M'_{Ejm} = \left[\frac{\frac{2}{\kappa_{Ejm}+1}\left(M'^{*}_{Ejm}\right)^2}{1-\frac{\kappa_{Ejm}-1}{\kappa_{Ejm}+1}\left(M'^{*}_{jm}\right)^2}\right]^{1/2}, \; j = 2, 3, \; m = 1, 2, \ldots, MM \tag{49}$$

where κ_{Ejm} is calculated by Eqs. (4), (5), and (6) for some initial guess on the trailing-edge static temperature.

The calculated area ratio of sudden expansion, $\left(\frac{A_2}{A_E}\right)_c$, where A_2 is the streamtube area at the downstream measuring station and A_E is the flow area at the trailing edge, is given by

$$\left(\frac{A_2}{A_E}\right)_{cjm} = \frac{M'_{Ejm}\cos\beta'_{Ejm}}{M'_{jm}\cos\beta_{jm}} \left[\frac{1+\frac{\kappa_{ajm}-1}{2} M'^{2}_{Ejm}}{1+\frac{\kappa_{ajm}-1}{2} M'^{2}_{jm}}\right]^{1/2} \left(1 + \kappa_{ajm} M'^{2}_{jm} \cos^2\beta_{jm}\right.$$

$$\left. - \kappa_{ajm} M'^{2}_{Ejm} \cos^2\beta'_{Ejm}\right) \tag{50}$$

for j = 2, 3, m = 1, 2, ..., MM where

$$\kappa_{ajm} = (\kappa_{Ejm} + \kappa_{jm})/2$$

The relative total pressure at the trailing edge is given by

$$P'_{Ejm} = P'_{jm} \left(\frac{A_2}{A_E}\right)_{cjm} \frac{M'_{jm}\cos\beta_{jm}}{M'_{Ejm}\cos\beta'_{Ejm}} \left[\frac{1+\frac{\kappa_{ajm}-1}{2} M'^{2}_{Ejm}}{1+\frac{\kappa_{ajm}-1}{2} M'^{2}_{jm}}\right]^{\frac{\kappa_{ajm}+1}{2(\kappa_{ajm}-1)}} \tag{51}$$

The static pressure at the trailing edge, based on the sudden area expansion equations for cylindrical stream surfaces, is given by

$$p_{Ejm} = p_{jm} \left(\frac{A_2}{A_E}\right)_{cjm} \frac{M'_{jm} \cos \beta_{jm}}{M'_{Ejm} \cos \beta'_{Ejm}} \left[\frac{1 - \frac{\kappa_{ajm} - 1}{2} M'^2_{jm}}{1 + \frac{\kappa_{ajm} - 1}{2} M'^2_{Ejm}}\right]^{1/2} \qquad (52)$$

The static temperature at the trailing edge is then given by an equation similar to Eq. (9) involving relative flow properties. An iteration cycle is set up for the calculations of Eqs. (49) through (52) until the static temperature at the trailing edge converges to the limit of the machine.

The calculated area ratio, the relative total pressure, and the static pressure at the trailing edge are printed on output data PAGE 5 in Appendix III.

The relative total pressure loss caused by sudden area expansion is given by

$$\omega'_{SEjm} = \frac{P'_{Ejm} - P'_{jm}}{P'_{1m} - p_{1m}} \qquad (53)$$

These quantities are printed on output data PAGE 6 in Appendix III.

2.13 DETERMINATION OF THE PROFILE LOSS

The overall relative total pressure loss, $\overline{\omega}'$, of Eq. (37) is assumed to be the sum of the shock loss, sudden area expansion loss, and profile loss so that the profile loss may be given by

$$\omega'_{Pjm} = \overline{\omega}'_{jm} - \omega'_{PSm} - \omega'_{SEjm} \qquad (54)$$

This may be put into a more standard form by defining the profile loss parameter, PL,

$$PL_{jm} = \frac{\omega'_{Pjm} \cos \beta_{jm}}{2\,\sigma_{1m}} \qquad (55)$$

where σ, the solidity, is assumed to have a distribution as a function of radius given by

$$\sigma = \frac{F_1}{r^2} + \frac{F_2}{r} + F_3 + F_4 r + F_5 r^2 \qquad (56)$$

where the coefficients are input data. The solidity, for use in Eq. (55), is calculated based on the radius of the center of the streamtube at the inlet ($j = 1$).

The results of the loss calculations, as a function of annulus height, are plotted for both the traverse data (j = 2) and the rake data (j = 3). Examples of these graphs are shown in Fig. 2. The points representing shock loss are plotted at the annulus height of the streamtube centers at the inlet measuring plane. The overall loss points are plotted at the annulus height of the streamtube centers for outlet measurements. For cylindrical stream surfaces, the points locating sudden expansion loss must be positioned at the same radial location as the streamtube centers for outlet flow measurements. The shaded area represents the computed profile loss.

2.14 CALCULATION OF THE BLOCKAGE FACTOR

The blockage factor is defined as the difference between the geometrical area at the trailing edge through which flow may pass and the calculated flow area divided by the geometrical area; i. e.,

$$B_j = \frac{A_E - (A_E)_{cj}}{A_E}, \quad j = 2, 3 \tag{57}$$

The geometrical area, A_E, through which flow may pass is the difference between the annulus area at the plane of the trailing edge and the area occupied by the blades. Assuming the distribution of the blade trailing-edge thickness, th, may be written in the form

$$th = \frac{E_1}{r^2} + \frac{E_2}{r} + E_3 + E_4 r + E_5 r^2 \tag{58}$$

then A_E is given by

$$A_E = \left(\pi - \frac{n}{2} E_4\right)\left(r^2_{Et} - r^2_{Eh}\right) - n\left[E_1 \frac{r_{Et} - r_{Eh}}{r_{Et}\, r_{Eh}} + E_2 \ln \frac{r_{Et}}{r_{Eh}} + E_3 \left(r_{Et} - r_{Eh}\right) + \frac{E_5}{3}\left(r^3_{Et} - r^3_{Eh}\right)\right] \tag{59}$$

where r_{Et} and r_{Eh} are, respectively, the radii of the outer and inner annulus walls at the plane of the trailing edge, and where n is the number of blades. The coefficients of Eq. (58), the radii r_{Et} and r_{Eh}, and the number of blades are all input data. The thickness, th, of Eq. (58) must be considered the arc length for use in these equations.

The streamtube area, A_2, at the downstream measuring planes is calculated by

$$A_{2jm} = \pi\left(r^2_{jiB} - r^2_{jiB+1}\right) \tag{60}$$

where j = 2, 3, and where the counter iB is varied so that the streamtube boundaries of the m-th streamtube are selected.

From the calculations of sudden area expansion for cylindrical stream surfaces, the streamtube area in the plane of the trailing edge is given by

$$(A_E)_{cjm} = \frac{A_{2jm}}{(A_2/A_E)_{cjm}} \tag{61}$$

so that the calculated flow area at the trailing edge is given by

$$(A_E)_{cj} = \sum_{m=1}^{MM} (A_E)_{cjm} \tag{62}$$

for j = 2, 3. The blockage factor may then be calculated by Eq. (57), and the results are printed on output data PAGE 5 in Appendix III.

2.15 CALCULATION OF THE DIFFUSION FACTOR

The diffusion factor, D, which is used as a blade loading parameter, may be given by

$$D_{jm} = 1 - \frac{M'_{jm}}{M'_{1m}} \sqrt{\frac{\kappa_{jm}\, t_{jm}}{\kappa_{1m}\, t_{1m}}} + \frac{M'_{\theta 1m} - M'_{\theta jm} \sqrt{\frac{\kappa_{jm}\, t_{jm}}{\kappa_{1m}\, t_{1m}}}}{2\sigma_{1m}\, M'_{1m}} \tag{63}$$

for j = 2, 3, m = 1, 2, ..., MM. The results of this calculation are printed on output data PAGE 6 in Appendix III.

SECTION III
DESCRIPTION OF INPUT DATA

The input data necessary for the operation of the computer program are, basically, an analytical description of the rotor, the locations of measuring positions, as well as the actual measurements taken. The measurement data may be entered in one of two ways: (1) listing of all measurements or (2) through the use of data arrays produced from the data reduction program for the supersonic compressor test program. If the measurements are listed, the values entered must represent the time average values of the measured flow properties at each measuring station. When the data arrays are entered, the program handles the simple averaging process where necessary.

For the use of this program it is implicitly assumed that outlet rake measurements and traverse measurements involving 5 and 11 radial positions are located at the same plane. Furthermore, the traverse of 13 radial positions may be located in an axial location different from the plane of the rake measurements (and traverse of 5 and 11 radial positions). Sample card formats for input data are given in Appendix III.

3.1 GROUP DATA

The classification of group data includes the analytical description of the rotor, some assumptions on the behavior of the flow model, and the locations of the measurement stations in each measuring plane. This data must be entered for each different rotor configuration, but they are required only once for each rotor configuration.

The cards are numbered below with the computer format; the names of the variables are given along with their description. Every card must be entered in the order given.

CARD 1. IPRNT, HEAD 1 FORMAT (1I3, 19A4)

IPRNT = 0, stop computation; therefore a blank card must be placed at the end of all input data.

= 1 for complete print out of the step by step computation.

= 2 for input and output tables only (see description of Output Data, Section IV).

HEAD 1 An identification of the rotor configuration. There are 76 spaces allowed.

CARD 2. MX, IX, RF, NB FORMAT (2I3, 1E12.4, 1I5)

MX Number of sets contained in the group. speed lines

IX = 0 if a static pressure tap is located on the compressor casing (tip) at the rotor trailing edge.

= 1 if no static pressure tap is located at the rotor trailing edge.

RF Recovery factor for the temperature probes.

NB Number of blades on the rotor.

CARD 3. R_{1t}, R_{1h}, R_{2t}, R_{2h}, R_{3t}, R_{3h} FORMAT (6E12.4)

R_{1t} Radius of the compressor casing (tip) at the plane of inlet flow measurements. (in.)

R_{1h} Radius of the compressor hub wall at the plane of the inlet flow measurements. (in.)

R_{2t} Radius of the compressor casing at the plane of the outlet traverse flow measurements. (in.)

R_{2h} Radius of the compressor hub wall at the plane of the outlet traverse flow measurements. (in.)

R_{3t} Radius of the compressor casing at the plane of the outlet rake flow measurements. This value must be entered only if $R_{2t} \neq R_{3t}$ or $R_{2h} \neq R_{3h}$; i.e., only if either or both the annulus walls converge or diverge. (in.)

R_{3h} Radius of the compressor hub wall at the plane of the outlet rake flow measurements. This value must be entered only if $R_{2t} \neq R_{3t}$ or $R_{2h} \neq R_{3h}$; i.e., only if either or both the annulus walls converge or diverge at outlet. (in.)

CARD 4. A_i FORMAT (6E12.3)

A_i Coefficients of a curve describing the inlet rotor blade angle β'_1 in radians as a function of radius from the axis in the form

$$\beta' = \frac{A_1}{r^2} + \frac{A_2}{r} + A_3 - A_4 r + A_5 r^2 + \arctan(A_6 r)$$

If any of the coefficients are zero, the proper 12 spaces required by the format may be left blank.

CARD 5. B_i FORMAT (5E12.3)

B_i Coefficients of a curve describing the suction surface expansion ϕ_{SS} as a function of radius from leading edge to passage entrance in radians. Coefficients are entered for a curve of the form

$$\phi_{SS} = \frac{B_1}{r^2} + \frac{B_2}{r} + B_3 + B_4 r + B_5 r^2$$

If any of the coefficients are zero, the proper 12 spaces required by the format may be left blank.

CARD 6. C_1, C_2 FORMAT (2E12. 3)

C_1 Passage shock loss adjustment coefficient. (0.9 is suggested. See Eq. (44))

C_2 Normal shock static pressure rise adjustment coefficient. (See Eq. (45))

CARD 7. D_i FORMAT (6E12. 3)

D_i Coefficients to describe the exit blade angle β'_E in radians as a function of radius. The assumed form is

$$\beta'_E = \frac{D_1}{r^2} + \frac{D_2}{r} + D_3 - D_4 r + D_5 r^2 + \arctan(D_6 r)$$

If any of the coefficients are zero, the proper 12 spaces required by the format may be left blank.

CARD 8. E_i FORMAT (5E12. 3)

E_i Coefficients of the curve to describe the blade trailing edge thickness, th, as a function of radius. Coefficients are entered for a curve of the form

$$th = \frac{E_1}{r^2} + \frac{E_2}{r} + E_3 + E_4 r + E_5 r^2$$

If any of the coefficients are zero, the proper 12 spaces required by the format may be left blank.

CARD 9. F_i FORMAT (5E12. 3)

F_i Coefficients of the curve to describe the blade solidity, σ, as a function of radius in the form

$$\sigma = \frac{F_1}{r^2} + \frac{F_2}{r} + F_3 + F_4 r + F_5 r^2$$

If any of the coefficients are zero, the proper 12 spaces required by the format may be left blank.

CARD 10. X_{1i} FORMAT (5E12. 3)

X_{1i} Fractional part of annulus height locating positions of inlet flow measurements. Listing is made from casing to hub, i. e., decreasing annulus height. Only 5 are entered.

CARD 11. $X5_{2i}$ FORMAT (5E12. 3)

$X5_{2i}$ Fractional part of annulus height locating traverse flow measurements for outlet when 5 positions are recorded. Listing is entered from casing to hub, i. e., decreasing annulus height.

CARD 12, 13, 14. $X11_{2i}$ FORMAT (5E12. 3)

$X11_{2i}$ Fractional part of annulus height locating traverse flow measurements for outlet when 11 positions are recorded. Listing is entered from casing to hub, i. e., decreasing annulus height.

CARD 15, 16, 17. $X13_{2i}$ FORMAT (5E12. 3)

$X13_{2i}$ Fractional part of annulus height locating traverse flow measurements for outlet when 13 positions are recorded. Listing is entered from casing to hub, i. e., decreasing annulus height.

CARD 18. X_{3i} FORMAT (5E12. 3)

X_{3i} Fractional part of annulus height locating rake flow measurements for outlet. Only 5 are entered. Listing is made from casing to hub, i. e., decreasing annulus height.

CARD 19. Z_i FORMAT (7E11. 4)

Z_i Axial position of the trailing edge of the rotor and the wall static pressure taps between the trailing edge and the plane of the downstream rake measurements, inclusive. The listing is entered in successive order. A maximum of 7 may be entered. If there are less than seven values, spaces are filled until the required number has been entered and blank spaces are left at the end of the card. (in.)

CARD 20. R_{ti} FORMAT (7E11. 4)

R_{ti} Radii of the casing walls at each axial position corresponding to the static taps as mentioned on CARD 19. This card is entered blank if R_{ti} is constant since this value has been entered on CARD 3. (in.)

CARD 21. R_{hi} FORMAT (7E11.4)

R_{hi} Radii of the hub wall at each axial position corresponding to the static taps as mentioned on CARD 19. This card is entered blank if R_h is constant since this value has been entered on CARD 3. (in.)

3.2 SET DATA

One card is required to give the number of subsets included in the set and to allow naming of the set. A set is usually interpreted as the data required to produce a constant rotor-speed operation characteristic. The card is placed before the subset data included in that set.

CARD 22. ISTART, HEAD 2 FORMAT (1I3, 19A4)

ISTART Number of subsets included in the set.

HEAD 2 An identification of the set. There are 76 spaces allowed.

3.3 SUBSET DATA

This classification of data includes the actual flow measurements. The data may be entered in alternative methods depending on whether data are to be listed in full or advantage is taken of the data arrays output by a data reduction program for the supersonic compressor test facility. A maximum of 12 subsets may be included with each set.

CARD 23. HEAD 3 FORMAT (20A4)

HEAD 3 An identification of the subset. There are 80 spaces allowed.

CARD 24. NN, MM, IPT, INP, RPM FORMAT (4I3, 1E12.4)

NN Number of measuring stations at the outlet traverse measuring plane.

MM Number of streamtubes sought; there may be a maximum of 10.

IPT = 0 if no plots are desired.

= 1 if only pressure loss plots are desired.

= 2 if only velocity ratio plots are desired.

= 3 if both velocity ratio and pressure loss plots are desired.

CARD 24. (Continued)

INP = 0 if input is by data array translation; CARDS 41 through 46 are expected to be supplied for each subset.

= 1 if input is by a full listing of averaged data; CARDS 25 through 40 are expected for each subset.

RPM Wheel rotations per minute; entered only if INP = 1.

CARDS 25 through 40 are expected if INP = 1.

CARD 25. p_{1t}, p_{1h}, p_{2t}, p_{2h}, p_{3t}, p_{3h} FORMAT (6E12.4)

p_{1t} Static pressure at outer casing at the inlet measuring plane. (lbf/in.^{2})

p_{1h} Static pressure at inner casing at the inlet measuring plane. (lbf/in.^{2})

p_{2t} Static pressure at outer casing for the outlet traverse measuring plane. (lbf/in.^{2})

p_{2h} Static pressure at inner casing for the outlet traverse measuring plane. (lbf/in.^{2})

p_{3t} Static pressure at outer casing for the outlet rake measuring plane. If the outlet traverse and rake measurements are made at the same plane, this value is not entered. (lbf/in.^{2})

p_{3h} Static pressure at inner casing for the outlet rake measuring plane. If the outlet traverse and rake measurements are made at the same plane, this value is not entered. (lbf/in.^{2})

CARD 26. p_{ti} FORMAT (7E11.5)

p_{ti} Outer casing static pressure entered in a manner corresponding to the Z's of GROUP DATA CARD 19. Leave blanks for unmeasured values. (lbf/in.^{2})

CARD 27. p_{hi} FORMAT (7E11.5)

p_{hi} Inner casing static pressures entered in a manner corresponding to the Z's of GROUP DATA CARD 19. Leave blanks for unmeasured values. (lbf/in.^{2})

CARD 28. P_{1i} FORMAT (5E12.3)

P_{1i} Inlet total pressure. (lbf/in.^{2})

CARD 29 (30, 31) P_{2i} FORMAT (5E12.3)

P_{2i} Outlet traverse total pressure. If NN = 5, one card is sufficient; if NN = 11 or 13, three cards are required. ($lbf/in.^2$)

CARD 32. P_{3i} FORMAT (5E12.3)

P_{3i} Outlet rake total pressure. ($lbf/in.^2$)

CARD 33. T_{1i} FORMAT (5E12.3)

T_{1i} Inlet total temperature. (°F)

CARD 34. T_{2i} FORMAT (5E12.3)

T_{2i} Outlet traverse total temperature. (°F)

CARD 35. T_{3i} FORMAT (5E12.3)

T_{3i} Outlet rake total temperature. (°F)

CARD 36. α_{1i} FORMAT (5E12.3)

α_{1i} Inlet absolute flow angle in degrees.

CARD 37 (38, 39) α_{2i} FORMAT (5E12.3)

α_{2i} Outlet traverse absolute flow angle in degrees. If NN = 5, one card is sufficient; if NN = 11 or 13, three cards are necessary.

CARD 40. α_{3i} FORMAT (5E12.3)

α_{3i} Outlet rake absolute flow angle in degrees. This card must be supplied only if NN = 13 (CARD 24).

CARDS 41 through 46 are expected if INP of CARD 24 equals zero.

CARD 41. α_{3i} FORMAT (5E12.3)

α_{3i} Absolute flow angles in degrees for the rake measurements. This card must be entered only if NN = 13; i. e., if NN = 13 (CARD 24).

CARD 42. P_{ti} FORMAT (5E12.3)

P_{ti} Traverse total pressures near the outer casing. This card is necessary only if NN = 11 or 13. Begin listing with the measurement nearest the outer casing. ($lbf/in.^2$)

CARD 43. P_{hi} FORMAT (5E12.3)

P_{hi} Traverse total pressures near inner casing. This card is necessary only if NN = 11 or 13. Begin listing with the measurement nearest the mainstream values. (lbf/in.^{2})

CARD 44. α_{ti} FORMAT (5E12.3)

α_{ti} Traverse absolute flow angles in degrees nearest outer casing. This card is necessary only if NN = 11 or 13. Begin listing with measurements nearest the outer casing.

CARD 45. α_{hi} FORMAT (5E12.3)

α_{hi} Traverse absolute flow angle in degrees near inner casing. This card is necessary only if NN = 11 or 13. Begin listing with measurement nearest the mainstream values.

Arrangement of the measured values for CARDS 42 through 45 are entered in such a manner that the mainstream measurements in the data arrays may be placed in between these values.

CARD 46. NX, COR(NX), M FORMAT (5(1I3, 1E12.3), 1I5)

NX Channel number to be corrected.

COR(NX) Correction to be substituted in channel NX.

M = 0 if 5 corrections are sufficient; i.e., one card.

= 1 if another card of corrections is necessary.

CARD 46 may be entered whenever data arrays are supplied. This allows substitution for incorrect values in the data arrays. The card must be entered blank if there are no corrections.

The complete program is actually divided into two main sections; the first simply prepares the data for entry into the main calculations described in Section II. In the process the prepared data are stored on tape and there exists the option of recalling this tape to run the second part of the program independent of the first to obtain a different output. This option is controlled by the following two cards.

CARD 47. ITAPE FORMAT (1I3)

ITAPE = 1 if input to second part is by cards.

= 2 if input to second part is by tape.

CARD 48. IPRNT FORMAT (1I3)

IPRNT = 0 to stop computation.

= 1 for complete printout of step by step computation.

= 2 for input and output tables only.

This option is useful in tracing errors. CARD 48 supercedes the IPRNT of CARD 1. These two cards are entered once, and a blank card follows to indicate program completion.

SECTION IV
DESCRIPTION OF THE OUTPUT DATA

The output of this program may include

1. a. Results of step by step calculations, or
   b. Six pages summarizing the main results.
2. Graphs prepared on a Calcomp plotter for:
   a. The ratio of the axial and tangential components of the absolute velocity downstream of the rotor to the maximum axial velocity in function of annulus height, or
   b. The composition of the overall relative total pressure loss according to the flow model in function of annulus height, or both.

In the following pages a brief description of Item 1. b. will be presented. An example of this output is shown in Appendix III. The results of the step by step calculations were used for checkout purposes and continue to be helpful in locating errors in input data; however, detailed description is unnecessary. Examples of the graphs are shown in Fig. 2.

Output data PAGE 1 presents a brief summary of the program input data.

Output data PAGE 2 presents the calculated boundaries and centers of the MM streamtubes for each measuring plane. These are presented both as the fractional part of annulus height and the radius in inches from the compressor axis.

Output data PAGE 3 presents a summary of the mass-averaged values of the streamtube flow variables in the absolute coordinate system for each of the measuring planes. Streamtubes are numbered from tip to hub in the first column. The second column repeats the streamtube center in the fractional part of the annulus height. The mass-averaged values of total pressure in units of $lbf/in.^2$ are presented in the third column. Similarly, the fourth column presents static pressure in units of $lbf/in.^2$; the fifth column, total temperature, in °R; the sixth column, absolute flow angle, in degrees. The one-dimensional average in each measuring plane is also presented for the flow variables.

Output data PAGE 4 presents some of the main calculated flow conditions and their one-dimensional averages. The first and second columns again present streamtube number and the location of the streamtube center in the fractional part of annulus height. The third and fourth columns present the streamtube absolute Mach number and the relative Mach number, respectively. The fifth column presents the streamtube absolute total enthalpy in units of Btu/lbm. The sixth column presents the relative flow angle at each of the measuring planes in degrees. The seventh column presents the blade angle in degrees calculated at the radius of the streamtube center. The eighth column presents the relative total pressure in $lbf/in.^2$; the ninth column, the relative total temperature in °R.

Output data PAGE 5 presents the total integrated mass flow in lbm/sec at each measuring plane along with the estimated percentage error in determining streamtube boundary and center location. It presents the calculations exhibiting the balance of the energy equation, various calculated values of static and total pressure at the rotor trailing edge, the results of the blockage factor calculation, and the streamtube area ratio from the sudden expansion calculations.

Output data PAGE 6 presents the principal results of the streamtube calculations and generally involves the use of measured data upstream and downstream of the wheel. In addition to the streamtube number as a reference, presented are the streamtube average and the one-dimensional average of the absolute total pressure ratio, adiabatic efficiency, the overall relative total pressure loss coefficient, the passage entrance Mach number, the passage shock loss based on this Mach number, the loss in relative total pressure attributable to sudden expansion, the calculated (arithmetically) profile loss, the profile loss parameter, and the diffusion factor.

Computation time for one case is approximately two minutes.

REFERENCES

1. Schwenk, F. C., Lewis, G. W., and Hartmann, M. J. "A Preliminary Analysis of the Magnitude of Shock Losses in Transonic Compressors." NACA RM E57A30, 1957.

2. Wennerstrom, A. J. and Olympios, S. "A Theoretical Analysis of the Blunt Trailing Edge Supersonic Compressor and Comparison with Experiment." ARL 66-0236, November 1966.

3. Salvage, J. W. "Investigation of the Flow through Supersonic Compressor Rotors of Blunt-Trailing-Edge Blade Design." University of Tennessee Space Institute, Tullahoma, Tennessee. 1969.

4. Carman, C. T. "Development of the Supersonic Compressor Test Facilities at the Arnold Engineering Development Center." AEDC-TR-65-169 (AD471021), October 1965.

5. Keenan, J. H. and Kaye, J. Gas Tables: Thermodynamic Properties of Air Products of Combustion and Component Gases, Compressible Flow Functions. John Wiley & Sons, Inc., New York, May 1960.

6. Lewis Research Center, Cleveland, Ohio. "Aerodynamic Design of Axial Flow Compressors." NASA SP-36.

7. Steinke, R. J. and Crouse, J. E. "Analytical Studies of Aspect Ratio and Curvature Variation for Axial-Flow-Compressor-Inlet Stages Under High Loading." NASA TN D-3959, May 1967.

8. Wennerstrom, A. J. "Flow Tables for Air (γ = 1.4) Passing an Abrupt Area Increase Oblique to the Flow Direction." ARL 64-10, January 1964.

APPENDIXES

I. ILLUSTRATIONS
II. INPUT DATA
III. OUTPUT DATA

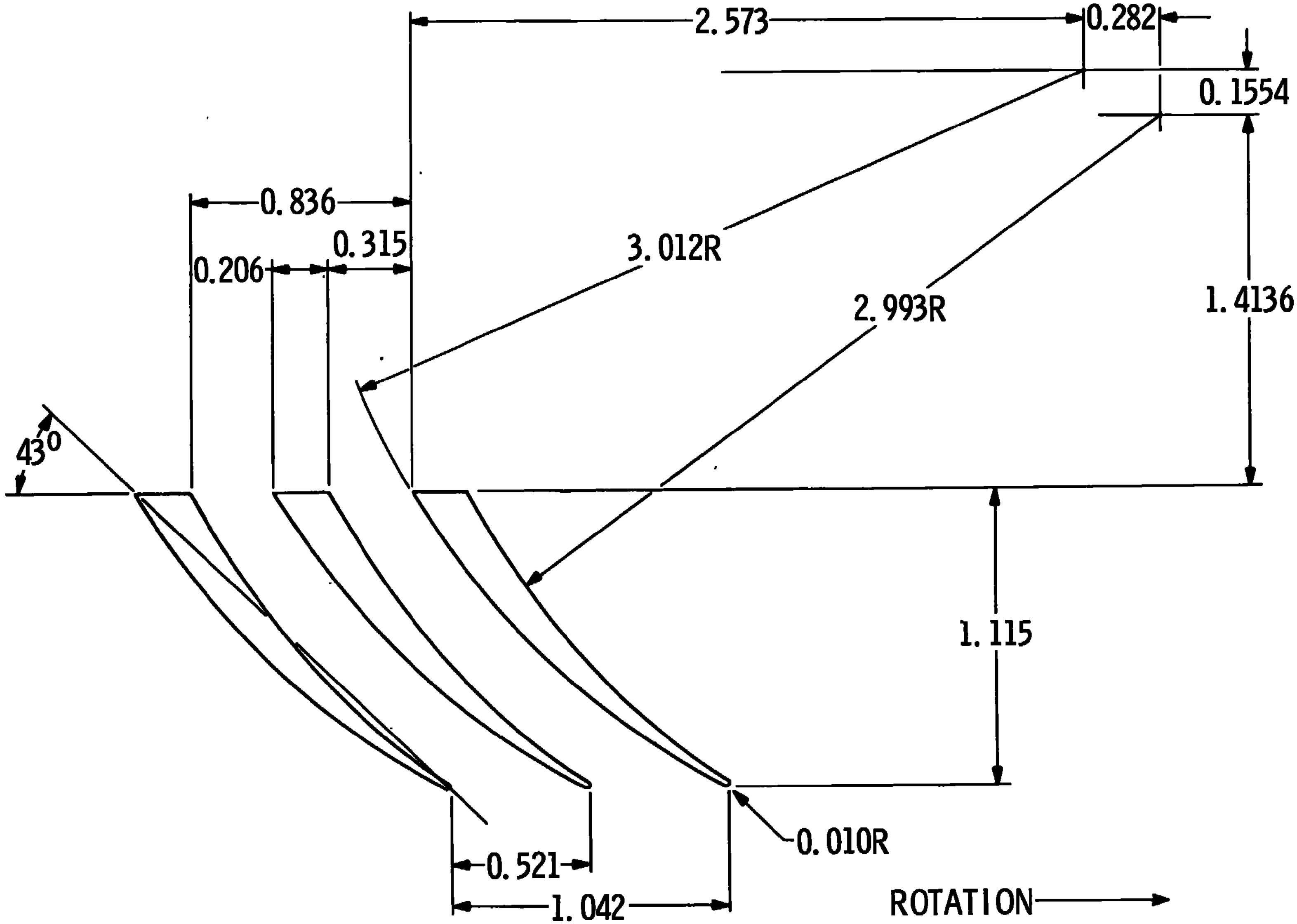

Fig. 1 Mean Radius Profile - Blunt-Trailing-Edge Blade No. 1

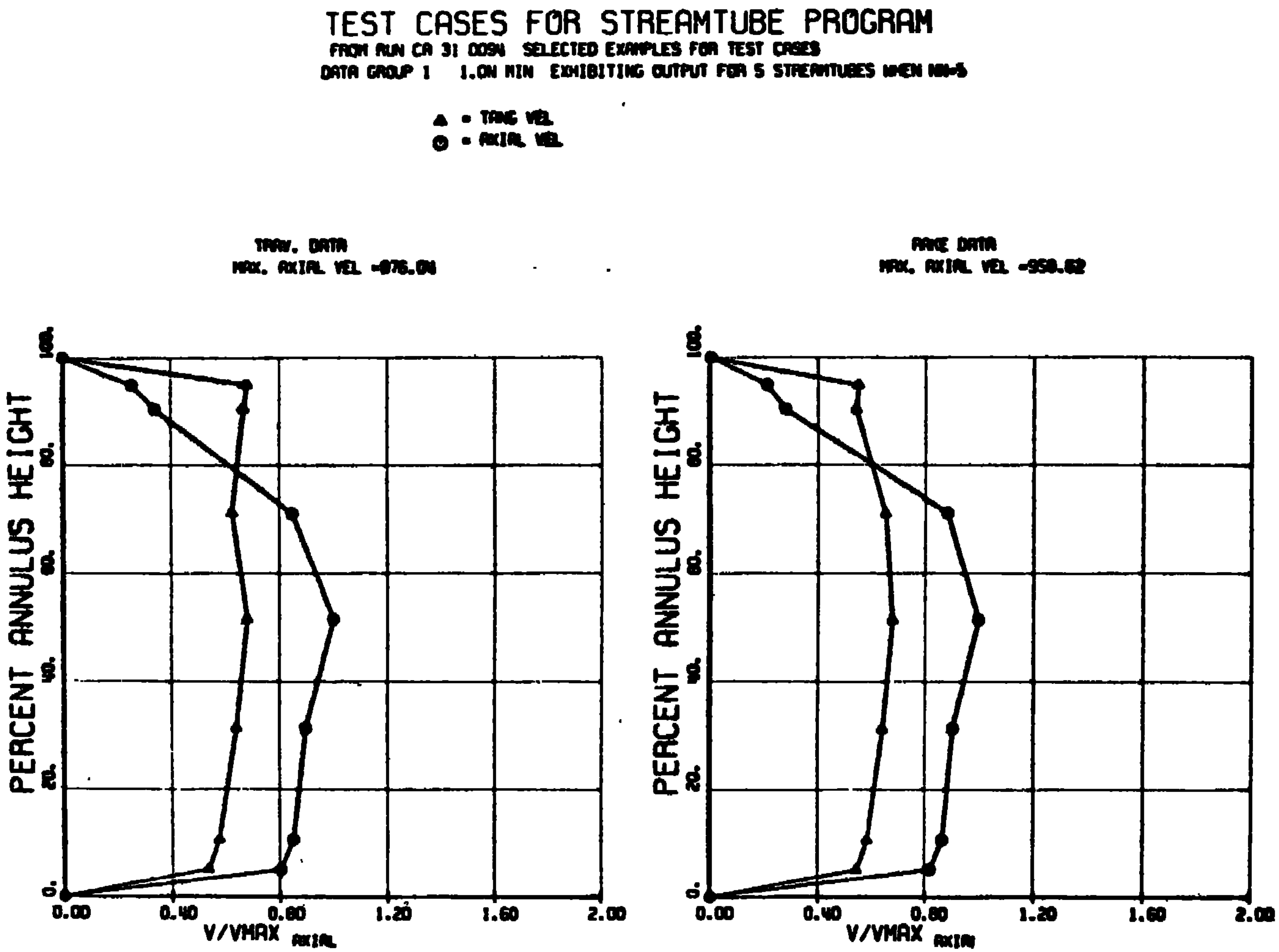

Fig. 2 Test Cases for Streamtube Program

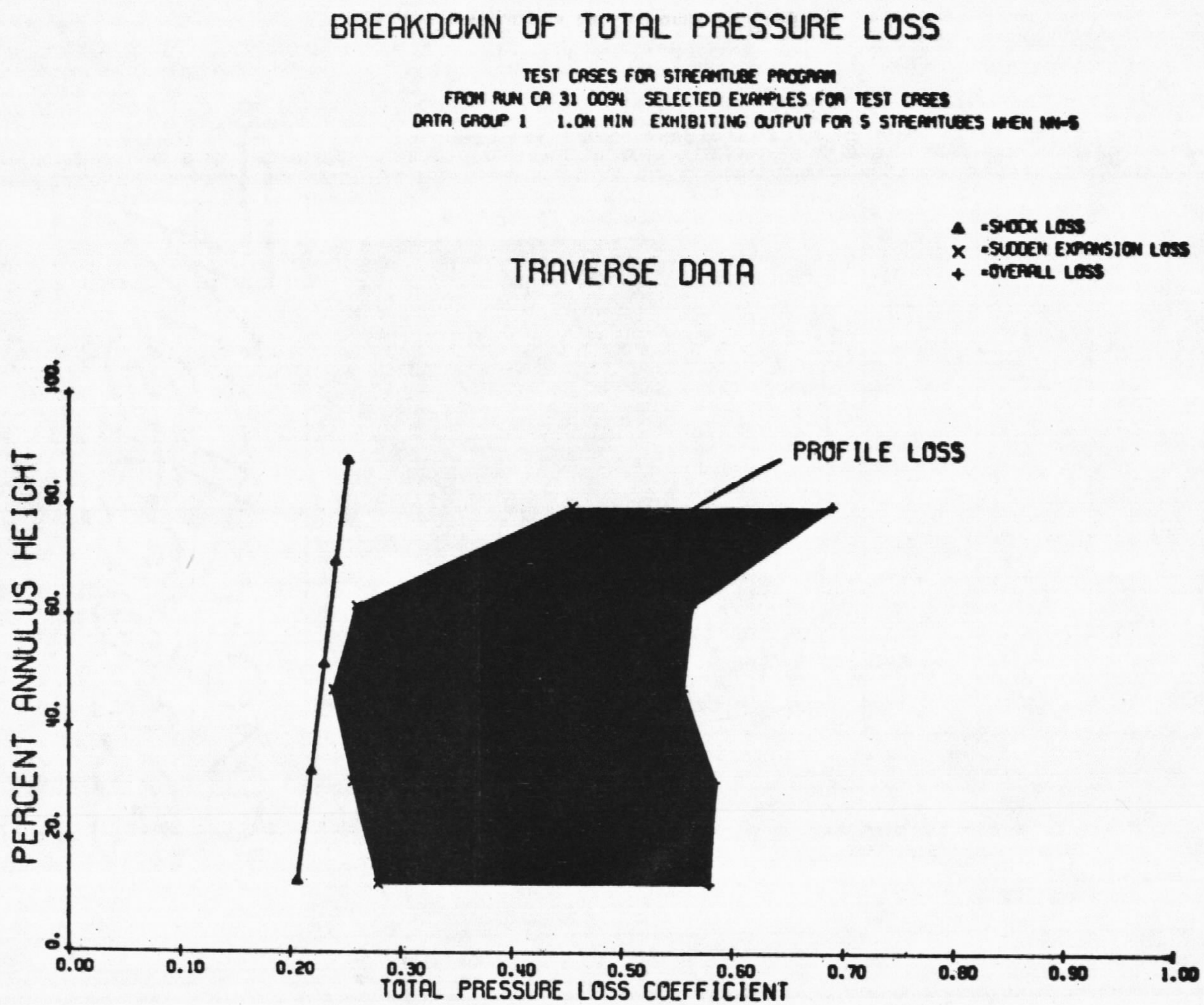

Fig. 2 Continued

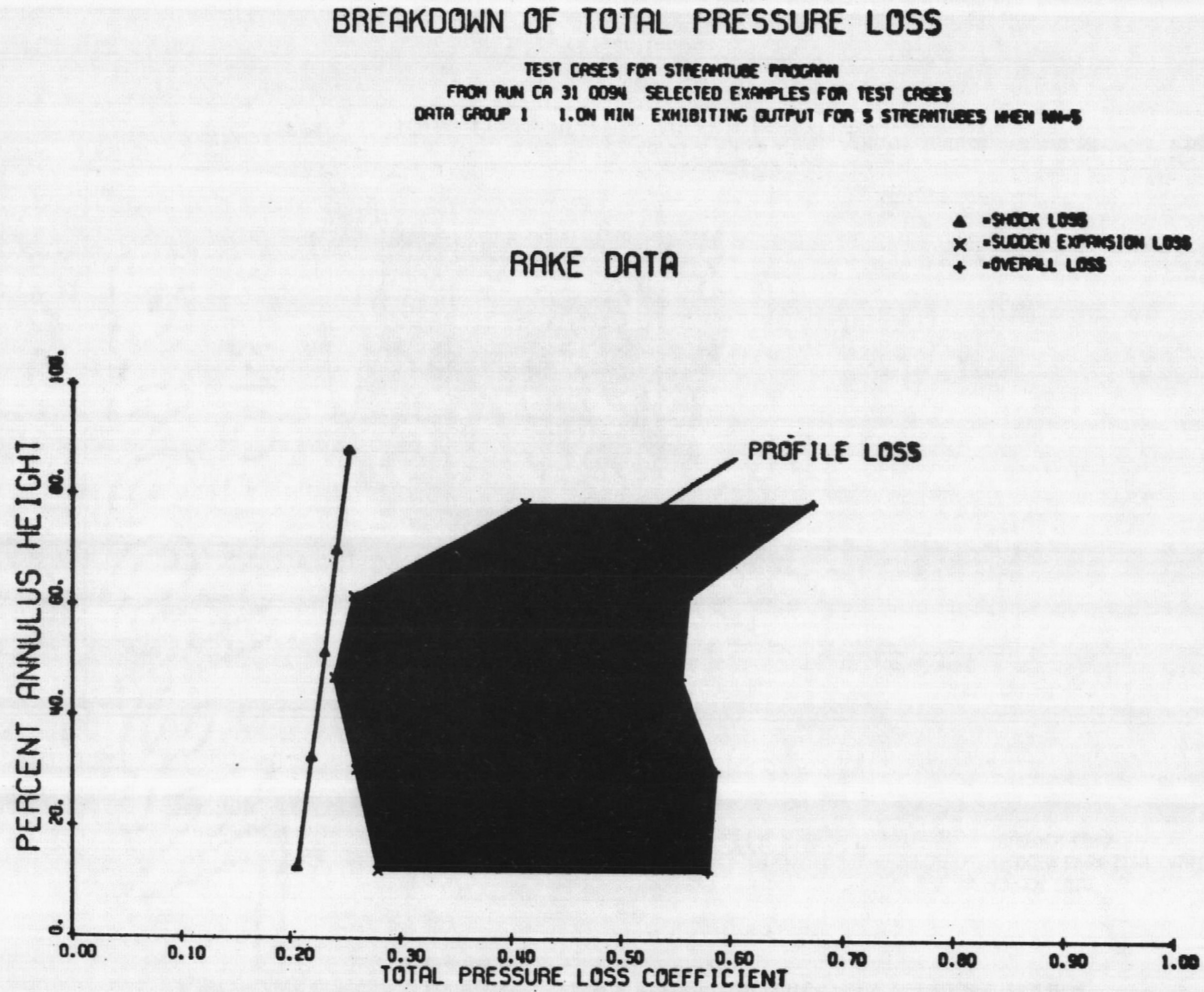

Fig. 2 Continued

TEST CASES FOR STREAMTUBE PROGRAM

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES

DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

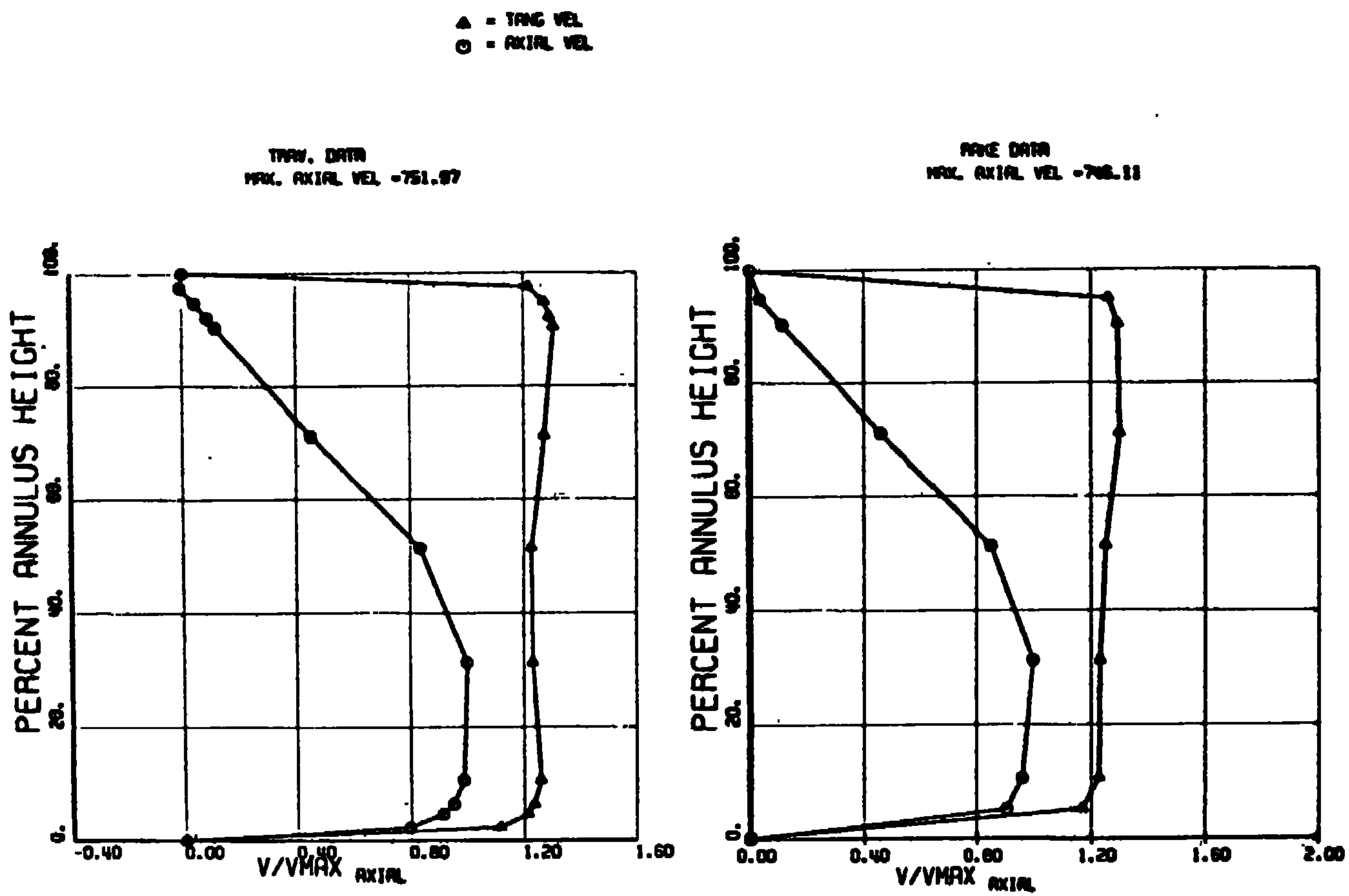

Fig. 2 Continued

BREAKDOWN OF TOTAL PRESSURE LOSS

TEST CASES FOR STREAMTUBE PROGRAM
FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

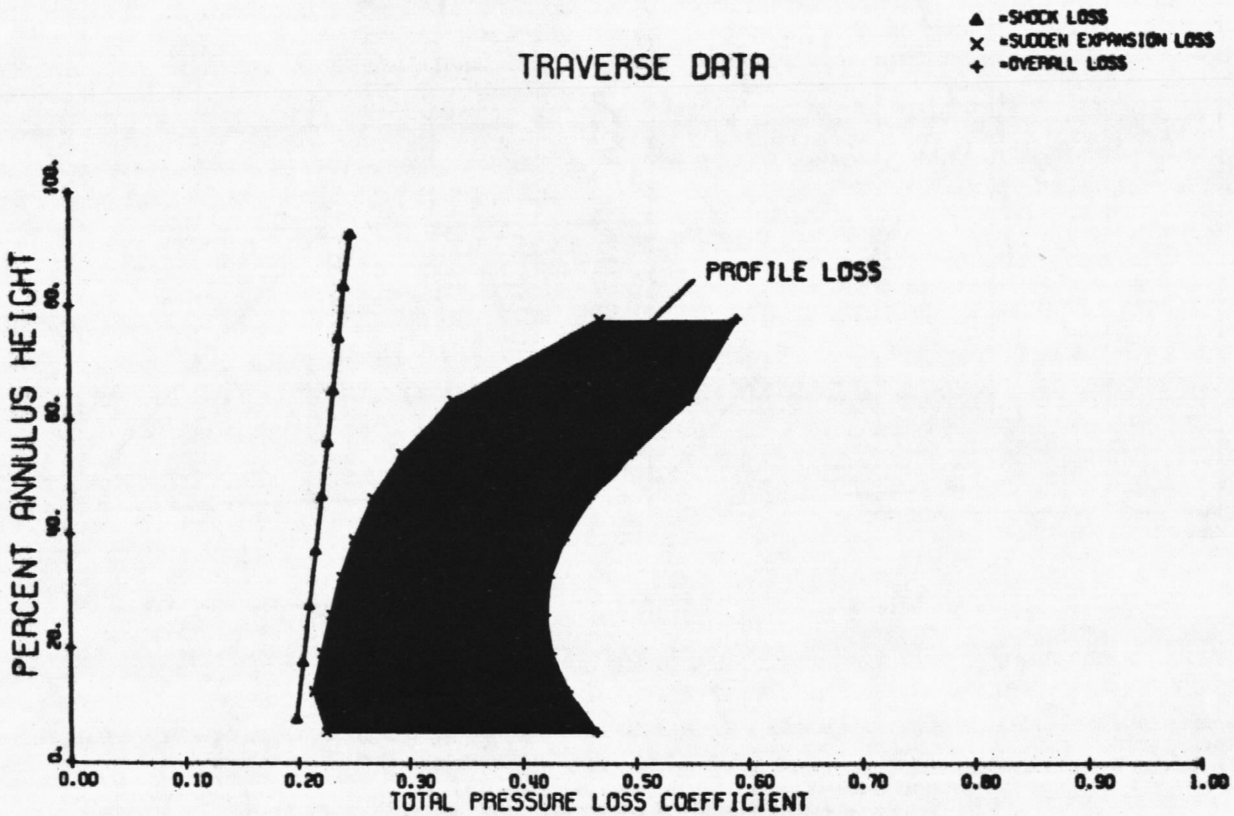

Fig. 2 Continued

BREAKDOWN OF TOTAL PRESSURE LOSS

TEST CASES FOR STREAMTUBE PROGRAM
FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

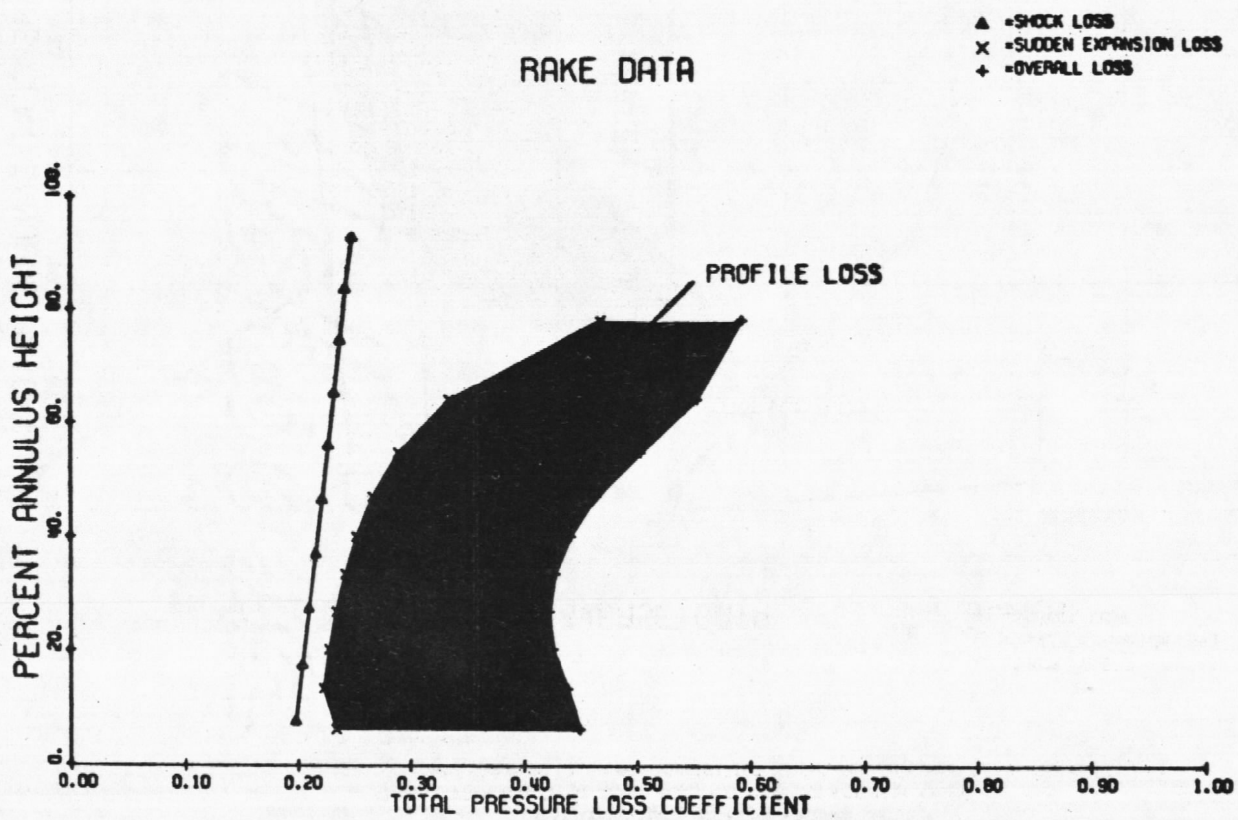

Fig. 2 Continued

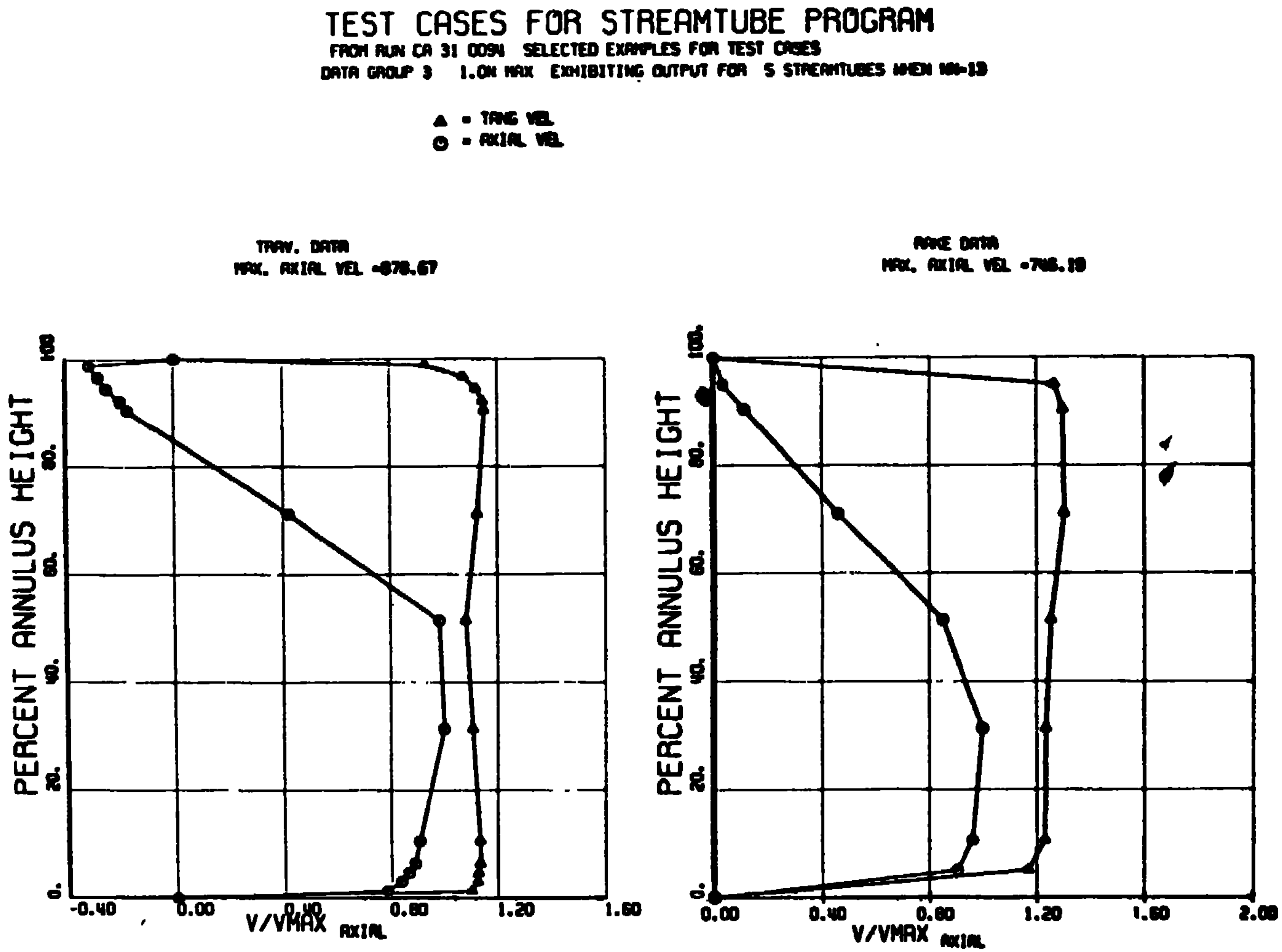

Fig. 2 Concluded

APPENDIX II
INPUT DATA

ARO, INC.
Arnold Air Force Station, Tennessee

CARD FORMAT

JOB TITLE
PROJECT NO.
SHEET 1 OF 4
PROGRAMMER Solomon -123

```
 2   TEST CASES FØR STREAMTUBE PRØGRAM
  1  0  .96         126

  11.0185     9.8435      11.0185     9.9
                                                            .1660483948

                         .148352987
  0.9          1.0

                                                            .0551999681
                                     .0135766051

                         6.443868243-.5072636189 .0173398234
   .905        .711        .514        .311        .105

   .904        .711        .513        .311        .105
   .975        .948        .921        .904        .711

   .513        .311        .105        .062        .045
   .022

   .988        .966        .944        .921        .904
   .711        .513        .311        .105        .063

   .046        .030        .013
   .904        .711        .513        .311        .105
```

DE 2

39

ARO, INC.
Arnold Air Force Station, Tennessee

CARD FORMAT

JOB TITLE ______________ SHEET 2 OF 4

PROJECT NO. ______________ PROGRAMMER ______________

```
    0.0         0.26        0.51        1.01        1.51        2.01
BLANK CARD

BLANK CARD
  3 FRØM RUN CA 31 0094  SELECTED EXAMPLES FØR TEST CASES

DATA GRØUP 1     1.ON MIN  EXHIBITING ØUTPUT FØR 5 STREAMTUBES WHEN NN=5
  5   5   3   1  16841.

    11.677      11.893      12.787      12.540
  8.87667    9.926661    9.95      10.82333    12.12333    12.78666

         8.176669    9.03      12.02      12.01333    12.54
    14.850      14.945      14.933      14.922      14.920

    16.250      20.500      23.750      21.300      19.900
    14.847      21.070      23.437      21.123      19.960

    67.47       65.73       65.08       66.00       68.29
    206.5       226.5       241.0       227.0       214.5

    209.05      226.65      229.63      226.16      215.42
    0.0         0.0         0.0         0.0         0.0

    63.0        36.4        34.2        35.4        34.0
DATA GRØUP 2     1.ON MAX  EXHIBITING ØUTPUT FØR 10 STREAMTUBES WHEN NN=11
```

DE 2

ARO, INC.
Arnold Air Force Station, Tennessee

CARD FORMAT

JOB TITLE ______________________ SHEET 3 OF 4

PROJECT NO. ______________________ PROGRAMMER ______________________

11	10	3	1	16710.			
11.770		11.983		21.540	19.763		
19.35933		18.9933	19.01	19.396	20.29932	21.54	
		17.04933	18.45332	18.93	18.98265	19.76332	
14.847		14.943		14.928	14.915	14.918	
29.75		30.70		31.00	31.25	31.50	
34.00		36.25		35.90	34.60	33.50	
30.10							
30.893		31.943		34.537	35.977	34.763	
70.12		67.16		66.74	67.31	69.23	
328.00		327.00		321.00	315.00	317.00	
322.37		321.32		316.34	312.31	305.12	
0.0		0.0		0.0	0.0	0.0	
90.4		88.1		86.2	85.0	70.5	
53.8		51.0		52.0	52.5	53.1	
54.5							

DATA GROUP 3   1.0N MAX   EXHIBITING ØUTPUT FØR 5 STREAMTUBES WHEN NN=13

13 5 2 1 16727.33

DE 2

ARO, INC.
Arnold Air Force Station, Tennessee

CARD FORMAT

JOB TITLE __________ SHEET 4 OF 4
PROJECT NO. __________ PROGRAMMER __________

11.7633	11.99	19.00665	18.47331	21.54	19.78331
19.371	19.03	19.00665	19.431	20.421	21.54
	17.131	18.47331	18.97331	19.02432	19.78331
14.855	14.94332	14.92666	14.915	14.91333	
25.3	27.5	28.25	28.5	28.5	
29.2	36.7	37.85	36.0	35.5	
34.8	34.1	32.55			
30.92	31.9833	34.5766	36.01	34.8066	
70.0663	67.0201	66.6014	67.3811	69.5948	
328.0	327.0	321.0	315.0	317.0	
323.0584	321.3847	316.2063	312.1817	305.5463	
0.0	0.0	0.0	0.0	0.0	
108.4	104.4	102.4	99.7	98.4	
69.4	47.7	47.9	51.3	51.9	
52.5	53.3	54.5			
85.0	70.5	55.8	51.0	52.0	

BLANK CARD

2	
2	

BLANK CARD

APPENDIX III
OUTPUT DATA

```
TEST CASES FOR STREAMTUBE PROGRAM                                                   PAGE    1

INPUT CONSTANTS

R
 9.84350  11.01850   9.90000  11.01850   9.90000  11.01850

A
 0.0      0.0        0.0      0.0        0.0       0.16605

B
 0.0      0.0        0.14835  0.0        0.0

C
 0.90000  1.00000

D
 0.0      0.0        0.0      0.0        0.0       0.05520

E
 0.0      0.0        0.0      0.01358    0.0

F
 0.0      0.0        6.44387  -0.50726   0.01734

FROM RUN CA 3I 0094   SELECTED EXAMPLES FOR TEST CASES
        DATA GROUP 1   1.0N MIN  EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=5

CONSTANTS FOR A SUBSET

P
 11.89300 11.67700 12.54000 12.78700 0.0      0.0

PBAR
14.8500 14.9450 14.9330 14.9220 14.9200 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
16.2500 20.5000 23.7500 21.3000 19.9000 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
14.8470 21.0700 23.4370 21.1230 19.9600 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

TEMP
527.140 525.400 524.750 525.670 527.960 666.170 686.170 700.670 686.670 674.170 668.720 686.320 689.300 685.830 675.090

ANGLE--DEGREES
 0.0     0.0     0.0     0.0     0.0     0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
63.000  36.400  34.200  35.400  34.000   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
63.000  36.400  34.200  35.400  34.000   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

RN=16841.0000000 00
```

TEST CASES FOR STREAMTUBE PROGRAM

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES

PAGE 2

DATA GROUP 1 1.0N MIN EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=5

CALCULATED BOUNDARIES AND CENTERS OF STREAMTUBES
RATIO TO PASSAGE HEIGHT AND RADIUS IN INCHES

STREAMTUBE NO.	INLET STREAMTUBE OUTER CENTER INNER		OUTLET TRAVERSE OUTER CENTER INNER		OUTLET RAKE OUTER CENTER INNER	
1						
	1.0000	11.0185	1.0000	11.0185	1.0000	11.0185
	0.8820	10.8798	0.7969	10.7914	0.7855	10.7785
	0.7912	10.7731	0.7004	10.6834	0.6941	10.6763
2						
	0.7912	10.7731	0.7004	10.6834	0.6941	10.6763
	0.6999	10.6659	0.6193	10.5926	0.6167	10.5897
	0.6079	10.5577	0.5436	10.5080	0.5431	10.5074
3						
	0.6079	10.5577	0.5436	10.5080	0.5431	10.5074
	0.5146	10.4481	0.4679	10.4233	0.4676	10.4230
	0.4198	10.3368	0.3878	10.3338	0.3873	10.3332
4						
	0.4198	10.3368	0.3878	10.3338	0.3873	10.3332
	0.3237	10.2238	0.3032	10.2391	0.3023	10.2381
	0.2261	10.1092	0.2144	10.1398	0.2132	10.1385
5						
	0.2261	10.1092	0.2144	10.1398	0.2132	10.1385
	0.1271	9.9928	0.1223	10.0368	0.1214	10.0358
	0.0	9.8435	0.0	9.9000	0.0	9.9000

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 1 1.0N MIN EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=5

SUMMARY OF MASS AVERAGED STREAMTUBE FLOW VARIABLES

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	TOTAL PRESSURE	STATIC PRESSURE	TOTAL TEMP	ABSOLUTE FLOW ANGLE
INLET						
	1	0.8820	14.7865	11.7029	528.2647	0.0
	2	0.6999	14.9434	11.7418	526.7777	0.0
	3	0.5146	14.9375	11.7819	526.2191	0.0
	4	0.3237	14.9228	11.8231	526.9851	0.0
	5	0.1271	14.8740	11.8653	529.0062	0.0
	AVERAGE		14.8928	11.7830	527.4506	0.0
OUTLET TRAVERSE						
	1	0.7969	18.8101	12.7366	680.7538	45.5406
	2	0.6193	21.8457	12.6960	696.1969	34.6389
	3	0.4679	23.0468	12.6561	701.4062	34.6209
	4	0.3032	21.2484	12.6146	689.9601	35.3193
	5	0.1223	19.7691	12.5701	678.4390	34.2794
	AVERAGE		20.9440	12.6547	689.3512	36.8798
OUTLET RAKE						
	1	0.7855	19.2960	12.7330	684.2809	43.5589
	2	0.6157	22.1139	12.6963	691.9601	34.8549
	3	0.4676	22.7793	12.6561	693.1563	34.6406
	4	0.3023	21.0746	12.6144	689.0272	35.3176
	5	0.1214	19.7785	12.5698	679.3307	34.2702
	AVERAGE		21.0084	12.6539	687.5511	36.5284

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES PAGE 4
DATA GROUP 1 1.0N MIN EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=5

CALCULATED FLOW CONDITIONS

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	ABSOLUTE MACH NUMBER	RELATIVE MACH NUMBER	TOTAL ENTHALPY	RELATIVE FLOW ANGLE	BLADE ANGLE	RELATIVE TOTAL PRESSURE	RELATIVE TOTAL TEMPERATURE
INLET									
	1	0.8820	0.5877	1.5807	126.7801	68.1746	61.0340	48.3568	741.4553
	2	0.6999	0.5970	1.5607	126.4237	67.5112	60.5495	47.1137	731.6788
	3	0.5146	0.5921	1.5317	126.2897	67.2583	60.0406	45.3034	722.8362
	4	0.3237	0.5863	1.4997	126.4734	66.9872	59.4998	43.3998	715.2469
	5	0.1271	0.5774	1.4640	126.9579	66.7729	58.9241	41.3657	708.8473
	AVERAGE		0.5881	1.5274	126.5850	67.3408	60.0096	45.1079	724.0129
OUTLET TRAVERSE									
	1	0.7969	0.7679	0.9341	163.4420	54.8433	30.7815	22.3548	715.0986
	2	0.6193	0.9160	1.0850	167.1701	46.0029	30.3154	26.6014	736.4295
	3	0.4679	0.9666	1.0842	168.4284	42.8055	29.9147	26.4946	729.8666
	4	0.3032	0.8965	1.0414	165.6640	45.3831	29.4751	25.0703	723.2945
	5	0.1223	0.8312	1.0280	162.8834	48.0754	28.9877	24.5838	721.9590
	AVERAGE		0.8757	1.0345	165.5176	47.4220	29.8949	25.0210	725.3296
OUTLET RAKE									
	1	0.7855	0.7944	0.9568	164.2931	53.0107	30.7516	22.9256	718.7466
	2	0.6167	0.9270	1.0876	166.1469	45.6151	30.3086	26.6877	730.0880
	3	0.4676	0.9563	1.0854	166.4357	43.5426	29.9139	26.5347	724.0073
	4	0.3023	0.8889	1.0397	165.4388	45.7681	29.4726	25.0186	723.5840
	5	0.1214	0.8317	1.0276	163.0986	48.0184	28.9854	24.5709	722.7000
	AVERAGE		0.8797	1.0394	165.0826	47.1910	29.8864	25.1475	723.8252

COMMENTS PAGE 5

	INLET	OUTLET TRAV.	OUTLET RAKE
MASS FLOW	20.976D 00	21.684D 00	21.562D 00
PERCENT MASS LOSS IN DETERMINING RADIAL POSITIONS	9.653D-09	2.047D-07	2.916D-07

PERCENT ENERGY UNBALANCE

STREAMTUBE	OUTLET TRAV		OUTLET RAKE	
	DELTA(H)	DELTA(E)/DELTA(H)	DELTA(H)	DELTA(E)/DELTA(H)
1	36.662	-1.45252D 01	37.513	-1.15322D 01
2	40.746	4.91617D 00	39.723	1.25551D 00
3	42.139	4.98455D 00	40.146	1.70298D 00
4	39.191	5.01874D 00	38.965	5.24703D 00
5	35.926	8.12771D 00	36.141	8.59795D 00
AVERAGE	38.933	1.70440D 00	38.498	1.05426D 00

	STATIC PRESSURE AT TRAILING EDGE			RELATIVE TOTAL PRESSURE AT TRAILING EDGE	
	FROM NORMAL SHOCK EQUATIONS	FROM SUDDEN EXPANSION EQUATIONS		FROM SUDDEN EXPANSION EQUATIONS	
STREAMTUBE	PASSAGE ENTRANCE	OUTLET TRAV.	OUTLET RAKE	OUTLET TRAV.	OUTLET RAKE
1	45.100	5.596	5.456	29.710	28.712
2	44.017	4.904	4.997	27.237	27.218
3	42.877	5.915	5.501	26.770	26.822
4	41.623	5.115	5.014	26.240	26.303
5	40.280	4.178	4.199	26.729	26.706

BLOCKAGE FACTOR--OUTLET TRAVERSE= -0.3142 OUTLET RAKE= -0.3456

CALCULATED SUDDEN EXPANSION AREA RATIO--ACTUAL EXIT BLADE AREA RATIO IS 1.3741

RADIAL POSITION	OUTLET TRAVERSE	OUTLET RAKE
1	1.437	1.299
2	0.904	0.903
3	0.927	0.914
4	0.954	0.954
5	0.938	0.939

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 1 1.0N MIN EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=5

RESULTS OF STREAMTUBE CALCULATIONS

INLET--OUTLET TRAVERSE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	1.2721	0.2455	0.6880	1.8562	0.2523	0.2007	0.2350	0.0227	0.4099
2	1.4619	0.3546	0.5621	1.8318	0.2415	0.0180	0.3026	0.0350	0.2967
3	1.5429	0.3942	0.5550	1.8060	0.2310	0.0082	0.3158	0.0381	0.2891
4	1.4239	0.3419	0.5843	1.7776	0.2194	0.0370	0.3279	0.0375	0.2993
5	1.3291	0.2985	0.5799	1.7471	0.2071	0.0727	0.3001	0.0323	0.2862
AVERAGE	1.40598	0.32693	0.59384	1.80373	0.23024	0.06732	0.29628	0.03312	0.31627

INLET--OUTLET RAKE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	1.3050	0.2663	0.6693	1.8562	0.2523	0.1579	0.2592	0.0262	0.3947
2	1.4798	0.3761	0.5589	1.8318	0.2415	0.0150	0.3025	0.0352	0.2993
3	1.5250	0.4020	0.5537	1.8060	0.2310	0.0086	0.3142	0.0375	0.2906
4	1.4122	0.3355	0.5857	1.7776	0.2194	0.0407	0.3256	0.0370	0.2997
5	1.3297	0.2972	0.5801	1.7471	0.2071	0.0724	0.3006	0.0324	0.2862
AVERAGE	1.41035	0.33543	0.58955	1.80373	0.23024	0.05890	0.30041	0.03365	0.31411

```
                    TEST CASES FOR STREAMTUBE PROGRAM

            INPUT CONSTANTS

        R
         9.84350  11.01850   9.90000  11.01850   9.90000  11.01850

        A
         0.0      0.0       0.0      0.0      0.0      0.16605

        B
         0.0      0.0       0.14835  0.0      0.0

        C
         0.90000  1.00000

        D
         0.0      0.0       0.0      0.0      0.0      0.05520

        E
         0.0      0.0       0.0      0.01358  0.0

        F
         0.0      0.0       6.44387  -0.50726  0.01734

        FROM RUN CA 31 0094   SELECTED EXAMPLES FOR TEST CASES
                DATA GROUP 2   1.ON MAX  EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

        CONSTANTS FOR A SUBSET

        P
         11.98300  11.77000  19.76300  21.54000   0.0      0.0

        PBAR
0.0      0.0      0.0      0.0     14.8470 14.9430 14.9280 14.9150 14.9180  0.0      0.0      0.0      0.0      0.0      0.0
0.0     29.7500 30.7000 31.0000 31.2500 31.5000 34.0000 36.2500 35.9000 34.6000 33.5000 30.1000  0.0      0.0      0.0
0.0      0.0      0.0      0.0     30.8930 31.9430 34.5370 35.9770 34.7630  0.0      0.0      0.0      0.0      0.0      0.0

        TEMP
529.790 526.830 526.410 526.980 528.900 787.670 786.670 780.670 774.670 776.670 782.040 780.990 776.010 771.980 764.790

        ANGLE--DEGREES
 0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
 0.0     90.400   88.100   86.200   85.000   70.500   55.800   51.000   52.000   52.500   53.100   54.500    0.0      0.0      0.0
 0.0      0.0      0.0      0.0     85.000   70.500   55.800   51.000   52.000    0.0      0.0      0.0      0.0      0.0      0.0

        RN=16710.0000000 00
```

TEST CASES FOR STREAMTUBE PROGRAM

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES

DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

CALCULATED BOUNDARIES AND CENTERS OF STREAMTUBES
RATIO TO PASSAGE HEIGHT AND RADIUS IN INCHES

STREAMTUBE NO.	INLET STREAMTUBE OUTER CENTER INNER		OUTLET TRAVERSE OUTER CENTER INNER		OUTLET RAKE OUTER CENTER INNER	
1						
	1.0000	11.0185	1.0000	11.0185	1.0000	11.0185
	0.9275	10.9333	0.7763	10.7683	0.7800	10.7724
	0.8819	10.8797	0.6960	10.6785	0.7010	10.6840
2						
	0.8819	10.8797	0.6960	10.6785	0.7010	10.6840
	0.8365	10.8264	0.6351	10.6103	0.6411	10.6171
	0.7911	10.7730	0.5842	10.5534	0.5911	10.5611
3						
	0.7911	10.7730	0.5842	10.5534	0.5911	10.5611
	0.7456	10.7195	0.5397	10.5037	0.5474	10.5122
	0.6999	10.6659	0.4998	10.4590	0.5081	10.4683
4						
	0.6999	10.6659	0.4998	10.4590	0.5081	10.4683
	0.6540	10.6120	0.4623	10.4170	0.4713	10.4271
	0.6079	10.5578	0.4263	10.3768	0.4358	10.3875
5						
	0.6079	10.5578	0.4263	10.3768	0.4358	10.3875
	0.5614	10.5032	0.3914	10.3378	0.4014	10.3489
	0.5146	10.4481	0.3574	10.2998	0.3677	10.3112
6						
	0.5146	10.4481	0.3574	10.2998	0.3677	10.3112
	0.4674	10.3927	0.3240	10.2624	0.3345	10.2741
	0.4198	10.3368	0.2910	10.2254	0.3016	10.2373
7						
	0.4198	10.3368	0.2910	10.2254	0.3016	10.2373
	0.3719	10.2805	0.2581	10.1887	0.2688	10.2006
	0.3236	10.2238	0.2252	10.1519	0.2359	10.1639
8						
	0.3236	10.2238	0.2252	10.1519	0.2359	10.1639
	0.2750	10.1667	0.1921	10.1149	0.2028	10.1269
	0.2261	10.1091	0.1587	10.0775	0.1693	10.0894
9						
	0.2261	10.1091	0.1587	10.0775	0.1693	10.0894
	0.1767	10.0512	0.1246	10.0394	0.1352	10.0512
	0.1270	9.9928	0.0898	10.0004	0.1001	10.0119
10						
	0.1270	9.9928	0.0898	10.0004	0.1001	10.0119
	0.0768	9.9337	0.0534	9.9598	0.0634	9.9709
	0.0	9.8435	0.0	9.9000	0.0	9.9000

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

SUMMARY OF MASS AVERAGED STREAMTUBE FLOW VARIABLES.

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	TOTAL PRESSURE	STATIC PRESSURE	TOTAL TEMP	ABSOLUTE FLOW ANGLE
INLET						
	1	0.9275	14.6811	11.7861	531.5419	0.0
	2	0.8365	14.8924	11.8050	529.8412	0.0
	3	0.7456	14.9329	11.8243	528.5614	0.0
	4	0.6540	14.9495	11.8436	527.8224	0.0
	5	0.5614	14.9412	11.8633	527.6409	0.0
	6	0.4674	14.9238	11.8835	527.7741	0.0
	7	0.3719	14.9174	11.9038	528.0092	0.0
	8	0.2750	14.9145	11.9244	528.5386	0.0
	9	0.1767	14.9152	11.9454	529.3882	0.0
	10	0.0758	14.8290	11.9660	530.5064	0.0
	AVERAGE		14.8897	11.8745	528.9624	0.0
OUTLET TRAVERSE						
	1	0.7763	30.9512	21.1668	791.2672	76.3946
	2	0.6351	32.4141	20.8912	788.1543	64.8474
	3	0.5397	33.6540	20.7213	785.5254	57.8011
	4	0.4623	34.8779	20.5723	782.5876	53.9044
	5	0.3914	35.7237	20.4461	780.5310	52.0950
	6	0.3240	36.1830	20.3365	779.5343	51.1369
	7	0.2581	36.3729	20.2306	779.2997	50.7772
	8	0.1921	36.3280	20.1188	779.7560	50.9443
	9	0.1246	36.0160	19.9903	780.9998	51.6622
	10	0.0534	33.4600	19.8575	782.8065	53.0264
	AVERAGE		34.5981	20.4331	783.0462	56.2589
OUTLET RAKE						
	1	0.7830	31.1804	21.1728	785.4903	76.6526
	2	0.6411	32.8269	20.9025	783.0721	65.3194
	3	0.5474	34.0746	20.7352	781.0166	58.3364
	4	0.4713	35.0766	20.5901	779.6713	54.2292
	5	0.4014	35.6826	20.4633	778.5305	52.3195
	6	0.3345	35.9406	20.3533	777.1745	51.2513
	7	0.2688	35.9334	20.2478	775.5259	50.7867
	8	0.2028	35.6723	20.1374	773.4523	50.8575
	9	0.1352	35.1043	20.0112	770.7163	51.5194
	10	0.0634	33.3180	19.8833	767.3171	52.1811
	AVERAGE		34.4810	20.4497	777.1967	56.3453

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES

DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

CALCULATED FLOW CONDITIONS

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	ABSOLUTE MACH NUMBER	RELATIVE MACH NUMBER	TOTAL ENTHALPY	RELATIVE FLOW ANGLE	BLADE ANGLE	RELATIVE TOTAL PRESSURE	RELATIVE TOTAL TEMPERATURE
INLET									
	1	0.9275	0.5689	1.5629	127.5659	68.6532	61.1529	47.4402	743.4767
	2	0.8365	0.5857	1.5604	127.1581	67.9562	60.9143	47.3446	737.6650
	3	0.7456	0.5871	1.5495	126.8513	67.7370	60.6723	46.6708	732.3088
	4	0.6540	0.5864	1.5368	126.6741	67.5697	60.4249	45.8831	727.5037
	5	0.5614	0.5835	1.5220	126.6306	67.4582	60.1707	44.9811	723.2484
	6	0.4674	0.5797	1.5063	126.6625	67.3633	59.9085	44.0359	719.2850
	7	0.3719	0.5769	1.4907	126.7189	67.2304	59.6381	43.1263	715.4062
	8	0.2750	0.5744	1.4747	126.8458	67.0773	59.3591	42.2166	711.8062
	9	0.1767	0.5721	1.4583	127.0495	66.9016	59.0713	41.3079	708.5116
	10	0.0768	0.5620	1.4373	127.3176	66.9819	58.7735	40.1588	705.4598
	AVERAGE		0.5777	1.5099	126.9474	67.4929	60.0086	44.3165	722.4671
OUTLET TRAVERSE									
	1	0.7763	0.7582	0.4999	190.2076	69.0954	30.7276	25.0942	745.5762
	2	0.6351	0.8186	0.5748	189.4506	52.7462	30.3570	26.1205	741.3188
	3	0.5397	0.8629	0.6545	188.8115	45.3744	30.1053	27.6136	742.6115
	4	0.4623	0.9030	0.7072	188.0974	41.2108	29.8997	28.7023	740.4272
	5	0.3914	0.9304	0.7330	187.5976	38.7638	29.7111	29.2092	737.1109
	6	0.3240	0.9465	0.7458	187.3555	37.2144	29.5309	29.4015	734.8601
	7	0.2581	0.9559	0.7482	187.2985	36.1163	29.3540	29.3148	732.9254
	8	0.1921	0.9597	0.7409	187.4093	35.2999	29.1764	28.9531	731.0246
	9	0.1246	0.9577	0.7230	187.7115	34.7479	28.9940	28.2964	729.2198
	10	0.0534	0.8973	0.6870	188.1506	38.2214	28.8011	27.2126	738.1598
	AVERAGE		0.8990	0.6814	188.2090	42.8790	29.6657	27.9918	737.3234
OUTLET RAKE									
	1	0.7800	0.7656	0.4975	188.8029	69.1890	30.7372	25.0620	738.2983
	2	0.6411	0.8305	0.5685	188.2152	52.4125	30.3730	26.0133	733.0213
	3	0.5474	0.8740	0.6486	187.7156	44.9840	30.1255	27.4962	734.8428
	4	0.4713	0.9074	0.7044	187.3887	41.1491	29.9237	28.6569	736.1385
	5	0.4014	0.9286	0.7310	187.1116	39.0609	29.7376	29.1785	735.2389
	6	0.3345	0.9399	0.7449	186.7821	37.8436	29.5588	29.4013	734.0343
	7	0.2688	0.9443	0.7488	186.3817	37.1264	29.3827	29.3551	732.1858
	8	0.2028	0.9427	0.7432	185.8781	36.8010	29.2053	29.0418	729.5112
	9	0.1352	0.9339	0.7270	185.2137	36.9336	29.0226	28.4310	725.8543
	10	0.0634	0.8921	0.7077	184.3885	39.3780	28.8281	27.7554	728.4797
	AVERAGE		0.8959	0.6822	186.7878	43.4878	29.6895	28.0391	732.7605

COMMENTS

	INLET	OUTLET TRAV.	OUTLET RAKE
MASS FLOW	20.712D 00	20.649D 00	20.383D 00
PERCENT MASS LOSS IN DETERMINING RADIAL POSITIONS	2.170D-08	3.085D-07	3.008D-07

PERCENT ENERGY UNBALANCE

STREAMTUBE	OUTLET TRAV		OUTLET RAKE	
	DELTA(H)	DELTA(E)/DELTA(H)	DELTA(H)	DELTA(E)/DELTA(H)
1	62.642	3.73912D 00	61.237	8.84891D-01
2	62.292	5.07486D 00	61.057	1.79082D 00
3	61.960	7.64899D 00	60.864	4.57517D 00
4	61.423	8.40244D 00	60.715	6.64438D 00
5	60.967	8.37112D 00	60.481	7.52568D 00
6	60.693	8.55066D 00	60.120	8.12458D 00
7	60.580	8.75285D 00	59.663	8.41381D 00
8	60.564	8.85172D 00	59.032	8.27021D 00
9	60.662	8.85254D 00	58.164	7.63554D 00
10	60.833	1.30323D 01	57.071	9.60106D 00
AVERAGE	61.262	8.12866D 00	59.840	6.34661D 00

	STATIC PRESSURE AT TRAILING EDGE			RELATIVE TOTAL PRESSURE AT TRAILING EDGE	
	FROM NORMAL SHOCK EQUATIONS	FROM SUDDEN EXPANSION EQUATIONS		FROM SUDDEN EXPANSION EQUATIONS	
STREAMTUBE	PASSAGE ENTRANCE	OUTLET TRAV.	OUTLET RAKE	OUTLET TRAV.	OUTLET RAKE
1	44.807	17.965	18.009	32.884	32.785
2	44.311	16.493	16.630	29.535	29.225
3	43.828	16.147	16.330	29.546	29.281
4	43.302	16.317	16.395	29.854	29.782
5	42.735	16.645	16.588	29.963	29.978
6	42.142	16.921	16.712	29.947	30.041
7	41.536	17.159	16.774	29.734	29.914
8	40.906	17.363	16.766	29.289	29.574
9	40.250	17.509	16.659	28.582	28.995
10	39.606	16.363	15.798	27.964	28.764

BLOCKAGE FACTOR--OUTLET TRAVERSE= 0.1843 OUTLET RAKE= 0.1891

CALCULATED SUDDEN EXPANSION AREA RATIO--ACTUAL EXIT BLADE AREA RATIO IS 1.3741

RADIAL POSITION	OUTLET TRAVERSE	OUTLET RAKE
1	4.229	4.252
2	1.963	1.945
3	1.490	1.478
4	1.305	1.304
5	1.223	1.232
6	1.181	1.197
7	1.158	1.181
8	1.145	1.180
9	1.142	1.195
10	1.257	1.278

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 2 1.0N MAX EXHIBITING OUTPUT FOR 10 STREAMTUBES WHEN NN=11

PAGE 6

RESULTS OF STREAMTUBE CALCULATIONS

INLET--OUTLET TRAVERSE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	2.1082	0.4814	0.5873	1.8442	0.2479	0.2185	0.1209	0.0073	0.7152
2	2.1766	0.5057	0.5459	1.8330	0.2421	0.0961	0.2077	0.0211	0.6605
3	2.2537	0.5327	0.4956	1.8219	0.2375	0.0555	0.2026	0.0237	0.5981
4	2.3331	0.5625	0.4581	1.8100	0.2325	0.0338	0.1917	0.0239	0.5570
5	2.3910	0.5851	0.4364	1.7972	0.2274	0.0228	0.1863	0.0240	0.5353
6	2.4245	0.5986	0.4236	1.7838	0.2220	0.0170	0.1847	0.0241	0.5219
7	2.4383	0.6044	0.4199	1.7701	0.2164	0.0134	0.1901	0.0251	0.5155
8	2.4358	0.6043	0.4251	1.7558	0.2105	0.0111	0.2035	0.0270	0.5162
9	2.4147	0.5976	0.4402	1.7409	0.2044	0.0097	0.2261	0.0300	0.5246
10	2.2564	0.5456	0.4657	1.7261	0.1989	0.0266	0.2402	0.0303	0.5373
AVERAGE	2.32321	0.56180	0.46980	1.78829	0.22396	0.05045	0.19539	0.02364	0.56817

INLET--OUTLET RAKE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	2.1239	0.4980	0.5892	1.8442	0.2479	0.2166	0.1247	0.0075	0.7194
2	2.2043	0.5254	0.5505	1.8330	0.2421	0.0904	0.2180	0.0223	0.6685
3	2.2819	0.5517	0.5009	1.8219	0.2375	0.0512	0.2122	0.0250	0.6060
4	2.3463	0.5734	0.4618	1.8100	0.2325	0.0331	0.1962	0.0245	0.5609
5	2.3882	0.5890	0.4400	1.7972	0.2274	0.0242	0.1885	0.0242	0.5373
6	2.4083	0.5992	0.4264	1.7838	0.2220	0.0199	0.1845	0.0239	0.5221
7	2.4088	0.6042	0.4215	1.7701	0.2164	0.0179	0.1873	0.0244	0.5142
8	2.3918	0.6058	0.4251	1.7558	0.2105	0.0176	0.1970	0.0256	0.5132
9	2.3536	0.6030	0.4386	1.7409	0.2044	0.0192	0.2150	0.0277	0.5201
10	2.2468	0.5784	0.4493	1.7261	0.1989	0.0358	0.2146	0.0266	0.5233
AVERAGE	2.31538	0.57283	0.47033	1.78829	0.22396	0.05257	0.19380	0.02317	0.56850

```
       INPUT CONSTANTS

    R
     9.84350  11.01850   9.90000  11.01850   9.90000  11.01850

    A
     0.0       0.0       0.0       0.0       0.0       0.16605

    B
     0.0       0.0       0.14835   0.0       0.0

    C
     0.90000   1.00000

    D
     0.0       0.0       0.0       0.0       0.0       0.05520

    E
     0.0       0.0       0.0       0.01358   0.0

    F
     0.0       0.0       6.44387  -0.50726   0.01734

   FROM RUN CA 31 0094   SELECTED EXAMPLES FOR TEST CASES
          DATA GROUP 3   1.0N MAX  EXHIBITING OUTPUT FOR  5 STREAMTUBES WHEN NN=13

    CONSTANTS FOR A SUBSET

    P
    11.99000  11.76330  18.47331  19.00665  19.78331  21.54000

    PBAR
  0.0      0.0      0.0      0.0      0.0     14.8550 14.9433 14.9267 14.9150 14.9133  0.0      0.0      0.0      0.0      0.0
  0.0     25.3000 27.5000 28.2500 28.5000 28.5000 29.2000 35.7000 37.8500 36.0000 35.5000 34.8000 34.1000 32.5500  0.0
  0.0      0.0      0.0      0.0      0.0     30.9200 31.9833 34.5766 36.0100 34.8066  0.0      0.0      0.0      0.0      0.0

    TEMP
529.736 526.690 526.271 527.051 529.265 787.670 786.670 780.670 774.670 776.670 782.728 781.055 775.876 771.852 765.216

    ANGLE--DEGREES
  0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
  0.0    108.400  104.400  102.400  99.700   98.400   69.400   47.700   47.900   51.300   51.900   52.500   53.300   54.500    0.0
  0.0      0.0      0.0      0.0      0.0     85.000   70.500   55.800   51.000   52.000    0.0      0.0      0.0      0.0      0.0

    RN=16727.330000D 00
```

TEST CASES FOR STREAMTUBE PROGRAM

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES

DATA GROUP 3 1.0N MAX EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=13

CALCULATED BOUNDARIES AND CENTERS OF STREAMTUBES
RATIO TO PASSAGE HEIGHT AND RADIUS IN INCHES

STREAMTUBE NO.	INLET STREAMTUBE OUTER CENTER INNER		OUTLET TRAVERSE OUTER CENTER INNER		OUTLET RAKE OUTER CENTER INNER	
1						
	1.0000	11.0185	1.0000	11.0185	1.0000	11.0185
	0.8820	10.8799	0.5997	10.5707	0.7010	10.6841
	0.7914	10.7734	0.5296	10.4924	0.5912	10.5612
2						
	0.7914	10.7734	0.5296	10.4924	0.5912	10.5612
	0.7002	10.6663	0.4678	10.4232	0.5082	10.4684
	0.6083	10.5582	0.4090	10.3574	0.4359	10.3875
3						
	0.6083	10.5582	0.4090	10.3574	0.4359	10.3875
	0.5150	10.4486	0.3501	10.2916	0.3677	10.3113
	0.4202	10.3372	0.2884	10.2225	0.3016	10.2373
4						
	0.4202	10.3372	0.2884	10.2225	0.3016	10.2373
	0.3240	10.2242	0.2236	10.1501	0.2360	10.1639
	0.2264	10.1095	0.1559	10.0743	0.1693	10.0894
5						
	0.2264	10.1095	0.1559	10.0743	0.1693	10.0894
	0.1272	9.9930	0.0847	9.9947	0.1001	10.0120
	0.0	9.8435	0.0	9.9000	0.0	9.9000

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES
DATA GROUP 3 1.0N MAX EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=13

SUMMARY OF MASS AVERAGED STREAMTUBE FLOW VARIABLES

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	TOTAL PRESSURE	STATIC PRESSURE	TOTAL TEMP	ABSOLUTE FLOW ANGLE
INLET						
	1	0.8820	14.7923	11.7904	530.6331	0.0
	2	0.7002	14.9414	11.8313	528.0566	0.0
	3	0.5150	14.9315	11.8732	527.5847	0.0
	4	0.3240	14.9158	11.9166	528.3295	0.0
	5	0.1272	14.8689	11.9609	530.2725	0.0
	AVERAGE		14.8900	11.8745	528.9753	0.0
OUTLET TRAVERSE						
	1	0.5997	35.3261	18.7550	787.6370	44.1672
	2	0.4678	37.0745	18.7288	785.2097	47.1127
	3	0.3501	37.7026	18.6667	781.9266	47.2920
	4	0.2236	37.1536	18.5922	780.3389	49.4239
	5	0.0847	35.3806	18.5180	782.7836	51.8884
	AVERAGE		36.5274	18.6521	783.5792	47.9768
OUTLET RAKE						
	1	0.7010	32.0421	21.0435	784.4047	70.9886
	2	0.5082	34.6129	20.6728	780.2107	56.2870
	3	0.3677	35.8447	20.4213	777.6833	51.7866
	4	0.2360	35.8381	20.2081	774.5021	50.8219
	5	0.1001	34.2526	19.9655	769.4693	51.8500
	AVERAGE		34.5181	20.4622	777.2540	56.3468

FROM RUN CA 31 0094   SELECTED EXAMPLES FOR TEST CASES

DATA GROUP 3   1.0N MAX   EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=13

CALCULATED FLOW CONDITIONS

	RADIAL POSITION	RATIO TO PASSAGE HEIGHT	ABSOLUTE MACH NUMBER	RELATIVE MACH NUMBER	TOTAL ENTHALPY	RELATIVE FLOW ANGLE	BLADE ANGLE	RELATIVE TOTAL PRESSURE	RELATIVE TOTAL TEMPERATURE
INLET									
	1	0.8820	0.5784	1.5637	127.3480	68.2897	61.0342	47.5144	740.9453
	2	0.7002	0.5870	1.5449	125.7302	67.6681	60.5503	46.3845	730.2055
	3	0.5150	0.5815	1.5157	126.6171	67.4379	60.0418	44.6044	721.5656
	4	0.3240	0.5754	1.4838	126.7957	67.1852	59.5007	42.7491	714.0634
	5	0.1272	0.5662	1.4483	127.2615	66.9865	58.9245	40.7759	707.6908
	AVERAGE		0.5777	1.5113	126.9505	67.5135	60.0103	44.4057	722.8941
OUTLET TRAVERSE									
	1	0.5997	0.9964	0.8924	189.3248	36.7854	30.2637	31.4403	761.9600
	2	0.4678	1.0385	0.8438	188.7347	33.1181	29.9144	29.8293	738.0934
	3	0.3501	1.0552	0.8386	187.9368	31.4138	29.6007	29.5720	729.6947
	4	0.2236	1.0463	0.7897	187.5510	30.4732	29.2613	28.0398	720.2598
	5	0.0847	1.0086	0.7262	188.1450	31.0035	28.8859	26.2919	719.3741
	AVERAGE		1.0290	0.8182	188.3385	32.5588	29.5852	29.0347	733.8744
OUTLET RAKE									
	1	0.7010	0.7998	0.5213	188.5391	60.0146	30.5304	25.3147	733.6599
	2	0.5082	0.8914	0.6762	187.5198	42.9679	30.0216	28.0645	735.0716
	3	0.3677	0.9345	0.7387	186.9057	38.5073	29.6478	29.3284	734.5577
	4	0.2360	0.9437	0.7467	186.1330	37.0272	29.2945	29.2416	730.9641
	5	0.1001	0.9138	0.7177	184.9109	38.1447	28.9277	28.1252	727.5257
	AVERAGE		0.8966	0.6801	186.8017	43.3323	29.6844	28.0149	732.3558

COMMENTS

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	INLET	OUTLET TRAV.	OUTLET RAKE
MASS FLOW	20.713D 00	21.684D 00	20.407D 00
PERCENT MASS LOSS IN DETERMINING RADIAL POSITIONS	1.047D-08	4.985D-07	1.500D-07

PERCENT ENERGY UNBALANCE

STREAMTUBE	OUTLET TRAV		OUTLET RAKE	
	DELTA(H)	DELTA(E)/DELTA(H)	DELTA(H)	DELTA(E)/DELTA(H)
1	61.977	1.32746D 01	61.191	5.67954D-01
2	62.004	7.11733D 00	60.790	5.35707D 00
3	61.320	5.96597D 00	60.289	7.69127D 00
4	60.755	4.01216D 00	59.337	8.21325D 00
5	60.884	5.07255D 00	57.649	8.45405D 00
AVERAGE	61.388	7.08852D 00	59.851	6.05672D 00

	STATIC PRESSURE AT TRAILING EDGE			RELATIVE TOTAL PRESSURE AT TRAILING EDGE	
	FROM NORMAL SHOCK EQUATIONS	FROM SUDDEN EXPANSION EQUATIONS		FROM SUDDEN EXPANSION EQUATIONS	
STREAMTUBE	PASSAGE ENTRANCE	OUTLET TRAV.	OUTLET RAKE	OUTLET TRAV.	OUTLET RAKE
1	44.634	14.986	17.175	31.843	30.271
2	43.661	16.979	16.345	29.920	29.494
3	42.540	17.664	16.627	29.600	30.058
4	41.314	17.988	16.750	28.052	29.798
5	40.008	17.623	16.222	26.326	28.894

BLOCKAGE FACTOR--OUTLET TRAVERSE= -0.2874 OUTLET RAKE= 0.1492

CALCULATED SUDDEN EXPANSION AREA RATIO--ACTUAL EXIT BLADE AREA RATIO IS 1.3741

RADIAL POSITION	OUTLET TRAVERSE	OUTLET RAKE
1	1.095	2.673
2	1.058	1.382
3	1.034	1.215
4	1.026	1.182
5	1.052	1.234

FROM RUN CA 31 0094 SELECTED EXAMPLES FOR TEST CASES PAGE 6
DATA GROUP 3 1.0N MAX EXHIBITING OUTPUT FOR 5 STREAMTUBES WHEN NN=13

RESULTS OF STREAMTUBE CALCULATIONS

INLET--OUTLET TRAVERSE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	2.3881	0.5779	0.3772	1.8404	0.2458	0.0113	0.1202	0.0162	0.4331
2	2.4813	0.6036	0.4213	1.8181	0.2359	0.0026	0.1828	0.0255	0.4717
3	2.5250	0.6233	0.4213	1.7926	0.2256	0.0009	0.1949	0.0274	0.4680
4	2.4909	0.6194	0.4589	1.7647	0.2143	0.0004	0.2442	0.0343	0.4950
5	2.3795	0.5852	0.5031	1.7348	0.2023	0.0012	0.2996	0.0413	0.5278
AVERAGE	2.45298	0.60187	0.43638	1.79010	0.22477	0.00327	0.20834	0.02893	0.47913

INLET--OUTLET RAKE

RADIAL POSITION	TOTAL PRESSURE RATIO	ADIABATIC EFFICIENCY	OVERALL LOSS	PASSAGE ENTRANCE MACH NO.	PASSAGE SHOCK LOSS	EXPANSION LOSS	PROFILE LOSS	PROFILE LOSS PARAMETER	DIFFUSION FACTOR
1	2.1661	0.5121	0.5748	1.8404	0.2458	0.1387	0.1903	0.0160	0.7040
2	2.3166	0.5633	0.4829	1.8181	0.2359	0.0414	0.2056	0.0250	0.5844
3	2.4006	0.5948	0.4335	1.7926	0.2256	0.0223	0.1856	0.0239	0.5297
4	2.4027	0.6060	0.4233	1.7647	0.2143	0.0180	0.1910	0.0248	0.5135
5	2.3036	0.5922	0.4438	1.7348	0.2023	0.0267	0.2148	0.0272	0.5217
AVERAGE	2.31793	0.57368	0.47166	1.79010	0.22477	0.04942	0.19746	0.02339	0.57068

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	UNCLASSIFIED
	2b. GROUP N/A

3. REPORT TITLE

COMPUTER ANALYSIS OF THE RELATIVE FLOW IN THE BLUNT-TRAILING-EDGE SUPERSONIC COMPRESSOR BLADING

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

April 1967 - December 1968 - Final Report

5. AUTHOR(S) (First name, middle initial, last name)

J. W. Salvage, ARO, Inc.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1969	68	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
F40600-69-C-0001	AEDC-TR-69-42
b. PROJECT NO. 7065	
c. Program Element 61102F	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A
d.	

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Available in DDC	Aerospace Research Laboratories, Office of Aerospace Research, Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

The computer program presented in this report has been designed specifically for the analysis of the blunt-trailing-edge supersonic compressor. Beginning with flow property measurements obtained in a nonrotating coordinate system, streamtube boundaries are determined at each measuring plane. Then mass-averaged values of the flow properties in each streamtube are translated to a coordinate system rotating with the compressor rotor, and a particular one-dimensional flow model is imposed on each streamtube to describe the flow process through the rotor. The flow model includes analysis of shock loss and sudden expansion loss leading to an estimate of the additional loss occurring within the flow field of the rotor. Various other calculations are presented which are aimed at the analysis of data for accuracy and consistency.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
axial-flow compressors						
compressor blades						
supersonic flow						
computerized simulation						
blunt bodies						

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